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CONTENTS

A HISTORY OF THE TORPEDO PART 3

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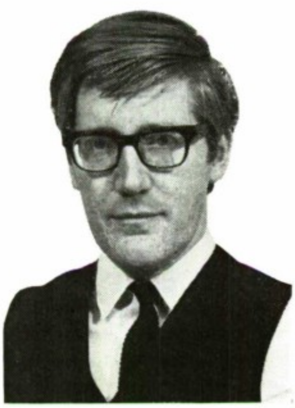

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Abstract

The problems of wartime torpedo production are described and the story of the electric torpedo is unfolded. This leads us on to the extensive German developments in homing torpedoes; these being the greatest advances since the invention of the thermal weapon in 1905.

World War II

It is not proposed to deal here with the tactical use of the torpedo in the last war because this demands a " history " of its own, nor will we follow in detail the development of the torpedoplane for the same reason. We will concern ourselves almost entirely with technical developments.

At the outbreak of war three hitherto unsuspected difficulties sprang to notice. These were the gross shortage of weapons, the failure to design weapons in materials which would be readily available in wartime and the appalling fuze failures. On the first count the situation was sufficiently desperate for the Allies to press into service old and obsolete weapons. In the United States, for example, the Mark 10 was pressed into service from

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This work has been undertaken as an extra-mural project and the opinions expressed here are those of the author and do not necessarily correspond to those of the Ministry of Defence (Navy).

retirement in order that submarines were not sent on missions with only a few weapons. As it was, the submarines often went on missions with less than a full load or had to await the arrival of a returning submarine in order to transfer from it its unused stock.

At the outbreak of war the reserve of torpedoes in the United States amounted to only a few hundred with a production rate of only 60 per month. Rapid expansion of production produced a gain over the expenditure rate by the end of 1942. During the period of the war up to the end of 1942 no less than 2,010 had been used compared with 2,382 manufactured and the crisis was over.

In Britain the production rate at the start of hostilities was about 80 per month which just about balanced the rate of expenditure. Because of the large number of torpedo types pressed into service at the start of the war it was inevitable that shortages should occur with some types. Production was rapidly increased to a figure of 440 per month by the end of 1942. Up to the same time a total of 2,308 weapons had been expended so that the initial shortage was soon brought under control.

A few words may be pertinent here on the manufacture of torpedoes during World War II. In Britain the main sources were the Royal Naval Torpedo Factory, Greenock and the Weymouth factory of Robert Whitehead (owned in fact by Vickers, Armstrong Ltd., since before the first World War). Further supplies were built by the Caton Engineering Company—mostly aircraft torpedoes of 18 in. diameter. With the 50 or so destroyers handed over to the Royal Navy in 1940 came a supply of Bliss torpedoes for use from the deck tubes. Add a few French weapons and we find quite an assorted armoury. Despite these many variations and the various old weapons forced into service in the early days of the war it is found that the greatest expenditure was by far with the 21 in. Mark VIII and the 18 in. Mark XII. The following table summarises the torpedo expenditure rates up towards the end of 1944. When analysed by date[26] it is found that three distinct peaks occur in the expenditure rate. These correspond closely with the North Africa campaign (December 1942), Sicily and Italy (Summer 1943) and France (1944).

The Bliss weapons listed were manufactured to British plans—Whitworth threads included—in order to meet demand. The $24\frac{1}{2}$ in. weapons were enriched air "specials" fitted to Rodney and Nelson. They were used from submerged bow tubes and were converted to natural air on the outbreak of war. The above two ships were fitted out in 1927 and they were indeed the last capital British warships to be fitted with torpedo tubes.

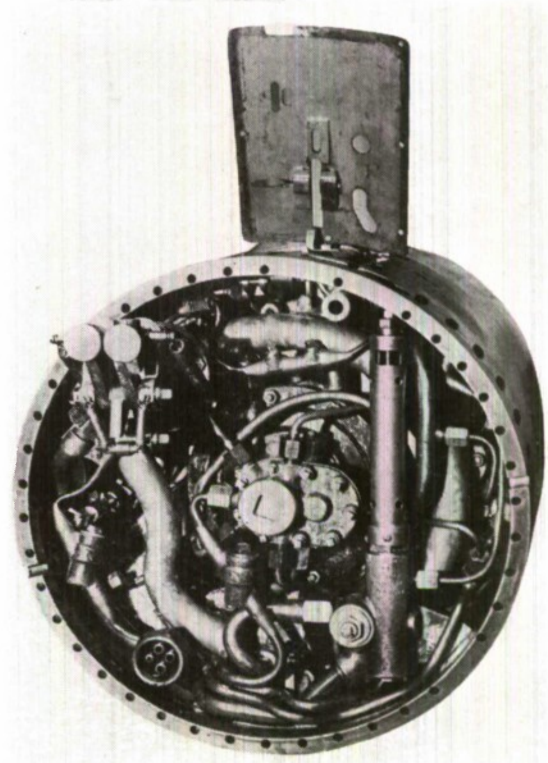

FIG. 29. An exercise in reticulation!

Torpedo production in the United States during the First World War was concentrated largely at the Bliss-Leavitt works and at the long established Naval Torpedo Station, Rhode Island. In 1919 the torpedo assembly plant was completed at Alexandria, Va., with a planned output of up to 3,000 weapons per annum. This factory appears to have been closed however by the 1920's but reopened when war threatened to engulf the United States in 1940. The weapons of the Second World War were made at Newport and Alexandria. The Bliss Company had reverted between the wars to its original production line of canning machinery products but the name still carried on as a symbol of that company's great achievements in the field of torpedo development. During the Second World War the Bliss firm returned to the torpedo world and, as we

TABLE 9. Torpedo expenditure up to September 1944 by type and origin

Diameter	*Mark*	*Origin*	*Number expended*
18 in.	VII*	Whitehead	1
	VIII*	R.N.T.F.	2
	XI*	R.N.T.F.	22
	XII	R.N.T.F.	693
	XII	Whitehead	395
	XII	Morris Motors	13
	XV	R.N.T.F.	440
	XV	Whitehead	97
	XV	Morris Motors	54
21 in.	II*	R.N.T.F.	8
	II*	Whitehead	13
	IV*	R.N.T.F.	178
	IV*	Whitehead	338
	V*	R.N.T.F.	86
	V*	Whitehead	112
	VII*	R.N.T.F.	9 (Converted to Natural Air)
	VIII	R.N.T.F.	1692
	VIII	Morris Motors	507
	VIII	Whitehead	1394
	VIII	Bliss	139
	IX	R.N.T.F.	252
	IX	Whitehead	109
	X	Whitehead	61
24½ in.	I*	R.N.T.F.	2 (Fired at ‘ Bismark ’)

Total expenditure up to September 1944 = 6447

*Not in wartime production

have seen, actually manufactured 21 in. Mark VIII torpedoes for Britain. Amongst the private companies manufacturing torpedoes for the U.S. Navy was the Pontiac division of General Motors.

FIG. 30. Fiume-Type tail components (c1939).

French torpedoes were originally made at Toulon; before 1900 all torpedoes were imported from Fiume. Robert Whitehead had opened a factory at St. Tropez at about the same time but exported most of its products to Turkey, Poland, Greece, Brazil and Holland. The " Societe des Torpilles de Saint-Tropez " took over the Whitehead factory and this was merged with the Schneider concern based at La Londe. The resultant organisation was the " Establissement de la Marine " at St. Tropez. This, as with the earlier firms, manufactured weapons to the designs of the torpedo workshops at the Toulon naval base. This latter was severely damaged during the war and in 1945 production was centralised at St. Tropez.

The Germans entered World World II with three proven torpedoes and it is of interest to see how the disarmament treaties were circumvented. As early as 1922 a German submarine design office had been set up in the Hague under a Dutch cover name of " Ingenieurskanteer voor Scheepbouw " and under this and similar covers in Spain and Finland the Germans were able to build up submarine expertise which enabled them to start their own building programme in 1935.

Similar tactics enabled them to develop torpedoes; the electric weapons having been tested and built in Sweden between 1923 and 1927. Following successful trials in 1929 the design was " frozen " to await full scale production in the late 1930's. It is remarkable that the British Admiralty had no knowledge of this development work until the weapons were used in 1939.

Aircraft torpedo trials could not be carried out without some notice being taken by the British and so the Germans bought Norwegian weapons from the Horten factory in March 1934. The Schwartzkopf concern, who it will be recalled were early pioneers in the torpedo world, had given up its torpedo interests in 1918 but in 1935 the Horten weapons were copied and a target of 600 production weapons by 1939 was set. This weapon proved to be a failure however and attempts were made to purchase Italian weapons from Fiume. This work did not get under way until late 1939 so that the Horten torpedo was the only aircraft torpedo in action at the start of World War II in Germany.

The number of torpedoes fired by the German Navy up to the end of January 1945 was just over 10,000, of which 7,000 were electric G7e types, 2,300 were G7a thermal types and 640 were acoustic homing weapons; the remainder being pattern running weapons.

Italian weapons were produced between the World Wars at the Fiume factory of Robert Whitehead. Following the death of Whitehead and all the important personalities of Fiume the firm in Britain was bought by Vickers, Armstrong Ltd. In 1922 the Fiume side of Whitehead's firm was reopened by the Orlando group who were a cover for the Italian Fascists. Weapons were also produced at Naples, originally by the De Luca-Daimler concern and then by the State Torpedo Factory. The Italian torpedoes of World War II carried either a prefix W to denote Fiume origin or prefix S.I. for Naples.

Japanese torpedoes, as we have already seen, were built at the Kure arsenal. The type numbers of Japanese torpedoes are related to the last two digits in the year on the Japanese calendar. This explains the appearance of the Type 92, etc., weapons — there were not 92 types of torpedo !

Having dealt briefly with the production of weapons in the last war we will next see how peace time plans sometimes go awry.

Production Problems in Wartime

We have seen how the problem of producing vast numbers of weapons was solved but this is not all the story. Weapons produced in peacetime were often simply not practical proposi-

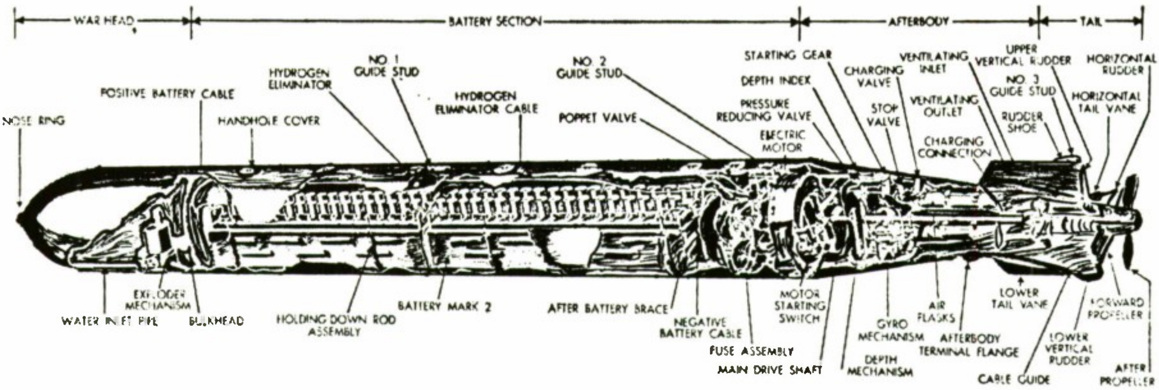

FIG. 31. Cutaway view of Torpedo, Mark 18.

tions for mass production in wartime. Bethell gives the following description of life in peacetime between the World Wars in the British torpedo factory:—

> *A few lads were kept to sweep the floors, make tea and go out for the evening paper; but the job was done by craftsmen with magic hands, who worked—not too ferociously—with ancient tools and fixtures that you had to know the trick of, in buildings made bright by grocers' calenders within and sweet peas without.*

TABLE 10.
Simplification of German G7a during wartime.

	1939	*1943*
Weight of Copper (Kg.)	370	169
Weight of Tin (Kg.)	61	22
Weight of Nickel (Kg.)	46	2
Man-hours per weapon	3 730	1 707
Cost (Reichmark)	24 000	13 500

Such techniques may be adequate in peacetime but in time of war such skilled labour and the time and materials are not available.

As an example we can look at the German *G7a* torpedo, this being a compressed air/decalin weapon with a piston engine, the design dating back to the mid-thirties. At the outbreak of war it was found to be impossible to build these weapons in sufficient numbers due to the scarcity of rare materials and skilled labour. As a result the finely designed weapon was simplified and cheapened with a small subsequent loss in performance. The final product was much superior for wartime use however. Table 10 briefly summarises the changes made to the weapon.

The demand for simple reliable torpedoes capable of being manufactured in large numbers led, amongst other developments, to the electric torpedo and this is therefore an appropriate place to deal with this weapon.

The Electric Torpedo

It will be recalled from earlier parts of this history that electric torpedoes were amongst the first types tested. Whether powered by electric current supplied *via* a trailing wire or by self-contained batteries (as in the Sims-Edison and Nordenfelt weapons respectively) their performance was comparable with compressed air weapons. The turn of the century saw the electric torpedo left far behind in performance however. Some rather desultory work continued in the United States resulting in an experimental battery driven torpedo in 1915. The weapon was only $7\frac{1}{4}$ in. in diameter (the smallest yet discovered by the author) and six feet long. It was expected to carry a warhead weighing a few pounds (the total weapon weight was only 60 lbs.) to a range of 3,800 yards at 25 knots. It seems most unlikely that such a performance would have been achieved however.

By 1918 this work, carried out by the Sperry Gyroscope Company, had come to a halt. The United States Navy were still maintaining an interest however and a design study in 1918 gave rise to an 18 in. diameter weapon in 1919. This work carried on slowly without much official support until 1931 when it ceased altogether.

The Germans, on the other hand, had successfully produced an electric weapon by 1918 and samples were issued to the fleet but never used because of the timely intervention of the Armistice. This weapon was capable of 28 knots to a range of 2,000 yards but after the Great War development continued in Sweden and Germany. The first indications that the Germans were using electric torpedoes came right at the start of the war. The *Royal Oak* was believed sunk at Scapa Flow by an electric weapon in 1939 and an electric weapon was recovered from the child evacuee ship s.s. *Volendam*; the torpedo fortunately being a "dud". The first complete sample was obtained in the early days of 1941 from the captured submarine *U.570.*

The weapon and its motor are described in detail elsewhere[20] but, in view of the rather novel nature of the weapon and its subsequent importance in the development of the homing torpedo a short description is justified here.

Known as the *G7e*, the weapon had a range of 8,000 yards and a speed of about 29 knots. The weapon had to be kept at 30°C for maximum range. Firing when cold reduced the range by about 1,400 yards. The batteries were heated only when the submarine was patrolling a target area. The batteries were lead-acid types and 26 cells each of 18 plates were used; the total battery weight being about 1500 lbs. The cells in each of the two batteries were connected in series. The motor was an 8-pole series wound D.C. machine, rated at 91 volts, 950 amps at 1,755 r.p.m. The weight of the motor was about 250 lbs. This same motor was used with only small modification in all the German electric weapons.

In other details the weapon was similar to its "thermal brother". The *TNT/HND/A1* warhead weighed 660 lbs. and the depth gear was conventional bellows and pendulum. Three forms of weapon existed. The earliest type, the *T2*, was in service at the start of the war and had a range of 5,400 yards at 30 knots. The *T3* and the *T3a* had the performance of 8,000 yards quoted above.

Apart from the homing torpedoes, of which we shall see more later, several special adaptations of the *G7e* appeared[27].

The requirement for pattern running electric weapons resulted in a redesign of the battery such that 125 amp. hours was obtained instead of the 93 amp. hours from the 13T210 battery fitted in the basic *G7e*. This pattern running weapon achieved 8,200 yards range and 30 knots. By reducing the battery size a low power torpedo was produced as the *T3b* which, when fitted to a *T3*, became the "Marder", a tandem weapon carrying a man as guidance system. We shall return to this and other man/torpedo combinations later.

The *T3b*, with its reduced performance of 4,400 yards and 18·5 knots was also fired from midget submarines. Perhaps the most curious of all the electric torpedoes developed during the last war was the *Dackel*, known also as the "slow-worm" or *T3d*. This had a speed of nine knots and a range of over 35 miles! This weapon was fired against ships in harbours or other restricted areas. It was used extensively against shipping in Seine Bay. Basically a pattern runner, the torpedo was fired into a bay and set to circle or zigzag for the rest of its four hours of endurance. The length of "slow-worm" was six feet more than the *G7e* making it protrude from the tubes on surface craft.

Moving on to a higher level of sophistication we come to the controlled torpedo. Most successful of these was the very aptly named *Spinne* (= spider) which was fired from coastal stations. A fine insulated wire was paid out and guidance instructions were transmitted down the wire to the weapon. By day the torpedo could be instructed to surface briefly and by night to flash a lamp in order that the operator could track its path. Observation posts were situated high on cliffs and up to three weapons could be controlled by each operator. Known also as *T*10, the weapon had a range of 5,400 yards and a speed of 30 knots. These weapons were set up along the French coast in 1944 but appear to have been of dubious effectiveness. They did inspire the British work on wire control of torpedoes, however, which led to the present wire-guided U.K. Mark 23.

The advantages of electric torpedoes were (and still are to some extent),

(a) tracklessness, allowing submarine attacks to be made with stealth,

(b) low cost of manufacture,

(c) employment of materials and labour not normally associated with torpedo production

and (d) suitability for mass production.

On the latter count, it is doubtful whether thermal weapons could have been produced at the rate of 1,000 per month—the rate for German electric torpedoes — with such economy of labour. In 1943 the electric weapons required 1,255 man-hours for production compared with 1,707 for the contemporary thermal weapon.

The British and United States navies had not thought too well of the electric torpedo at the start of the war on account of its relatively poor propulsive performance. The British navy had no particular use for trackless torpedoes—not as great a use as the Germans and Americans. The Americans were the first to see the advantages in the war against Japanese convoys and, on obtaining a captured *G7e* in 1940, orders were sent to Westinghouse, Inc., to produce a copy. Most accounts of the American electric torpedo quote a high degree of co-operation between industry and the U.S. navy resulting in the American version of the *G7e* being in service "within six months". In fact it was 1942 before work started and troubles arose in many quarters. Certain parts of the torpedo were not understood and others could not be produced. A "Chinese copy" proved impossible and work faltered. An inquiry was set up to investigate the delay in producing the Mark 18 (as the U.S. version was to be designated) and the following report was made by the Inspector General:—

The delays encountered were largely the result of the manner in which the project was prosecuted and carried out. These difficulties indicated that the liaison officers at the Bureau of Ordnance failed to follow up and properly advise the Westinghouse Company and Exide Company during the development of the Mark 18 torpedo. The Torpedo Station personnel competed with rather than co-operated with, the development of the Mark 18 . . .

These remarks contrast sharply with the glowing tributes paid in the several semi-official histories of the Mark 18 project. However, be that as it may, the U.S. electric torpedo, numbered the Mark 18, entered service in late 1943. It was regarded with suspicion at first but rapidly gained popularity. It had the advantages of tracklessness and reliability which offset the poor speed performance. During 1944 we find that 30% of U.S. torpedoes fired were electric and by the end of the war the proportion was 65%.

The problem of ventilation was vexing in U.S. submarines. The hydrogen generated in the torpedoes during storage had to be purged regularly. Fires sometimes broke out and one such incident on the U.S.S. *Flyingfish* caused such a ferocious blaze that the torpex warhead melted and ran out of the torpedo!

The first British work on electric torpedoes started soon after the first pieces of *G7e* arrived at the Royal Naval Torpedo Factory, Greenock in 1940. Only a low priority was given however because of the lack of tactical requirement for slow weapons. In 1942 the available drawings and hardware were sent to British Thompson Houston, Ltd., at Rugby with instructions to investigate the possibilities of building a similar weapon. This upsurge of interest came as a result of a tactical requirement for trackless weapons in the Mediterranean. The first torpedoes were received for trials in May 1943. B.T.H. eventually worked up a production rate of 25 weapons per month. (Compare this with the German rate of 1,000 per month!)

This torpedo, numbered the Mark 11, was about to enter service in the Mediterranean when the Italians capitulated. Stocks were then moved out to the Pacific arena where they arrived just too late to be used against the Japanese. Thus, the first British electric torpedo failed to be fired in anger.

First Homing Torpedoes

The electric weapons laid open the means of producing homing torpedoes because they were quieter than the thermal types—this being almost entirely on account of the former's lower speed. The Germans, being the first nation to mass produce an electric torpedo, were also the first to produce a homing torpedo.

Experimental work in support of the homing torpedo started in Germany around the mid-nineteen thirties with simple measurements of the noise of various ships and weapons. It was soon evident that a basic limitation on the homing ability of a weapon using acoustic methods was the "self-noise" in the homing transducers; that is to say, the background noise due to the motion of the weapon itself. Measurements of the self-noise showed that the level was almost independent of the weapon being used, *i.e.* whether a thermal engined *G7a* or an electric *G7e*, but depended very much on the speed of the weapon. Later work showed that the noise originated at the propellers and improved propeller design lowered the self-noise, but initially it was calculated that a torpedo would only be able to home from a reasonable distance onto a ship if the torpedo speed did not exceed 25 knots. Therefore, a *G7e* was modified to run at this speed and a simple homing device was fitted in the nose. (Later in the war the Allies came to the same conclusion regarding weapon speed but had no weapon capable of such a low speed nor a tactical requirement for slow torpedoes). The first homing torpedo was issued to the German fleet in January 1943 and was the T4, also known as *FALKE* (= Falcon). About 100 *T4* weapons were made and about 30 were used. They were soon replaced by the *T5* weapon which was given the code name during development of *ZAUNKONIG* (= Wren). It was also known to the Allies as *GNAT* (German Naval Acoustic Torpedo), an altogether much more appropriate name.

Gnats appeared in two basic forms, namely the flat and the rounded nose types. Both types used an amplitude comparison system known as "*amsel*". Initial experiments, carried out over many years beginning in about 1936, eventually resulted in the *T5* or *GNAT* having a speed of 25 knots. This was chosen as the upper speed because of the deliterious effects of self-noise. This speed gave the weapon a capability against ships having speeds in the range 12 to 19 knots, the lower speed being at the lower limit for noise sufficient to activate the *T5*'s passive homing system.

The flat-nosed weapons, the nose of which is illustrated in Fig. 32, carried four magnetostriction hydrophones wired in alternating pairs. A phase delay was introduced between the sets of pairs so that the electrical output

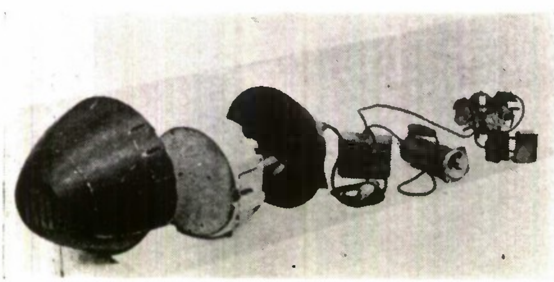

FIG. 32. Nose and Homing Unit of German "GNAT" Torpedo (1943).

was a maximum for sound arriving at ±25° to the axis of the weapon in the horizontal plane. The amplitude in each pair of hydrophones was compared by switching to a comparator at 100 cycles per second. The rudders were then swung to steer the weapon towards the side receiving the greatest noise. In the round-nose weapon a bakelite cap was used to protect the hydrophones. Only two of these were used, each being placed behind a baffled funnel to give maximum sensitivity at ±25° as for the flat nose system. The funnels and the cap were filled with glycerine and ethylene glycol to give good acoustic transmission to the hydrophones.

Due to an error it is widely believed that over 6,000 *T5* weapons were fired during the war. In fact, careful research shows that 640 were fired with a hit rate of 6%. The Germans claimed a rate of 53%. Over 2,500 *T5's* were test-fired in development.

Successes with *ZAUNKONIG* led to the development of *ZAUNKONIG* 2. The intended improvements were:

(a) Variable enabling ranges allowing escorts to be passed by thus putting merchant shipping at risk.

(b) Increased range. (The new batteries were never actually brought into service and the range remained at 6,230 yards.)

(c) Improved propeller design. This reduced the self-noise and allowed ships with speeds down to 9 knots to be detected.

(d) The ability to be fired at depths down to 170 feet (compared with the maximum depth of 49½ ft. for the *T5*).

(e) Resistance to countermeasures. This latter was included because of the success of the *FOXER*, a towed noise-maker deployed by Allied shipping, which seduced the passive weapons away from the ship. The *ZAUNKONIG 2*, or *T11* as it was also called, employed an acoustic "dead spot" in the azimuth sensitivity pattern at 20°. The weapons were fired at about 20° on the target's bow. The noise of the ship was not picked up until very late in the attack and then the weapon was programmed to execute a sharp turn which, hopefully, resulted in a hit on the ship.

Although the *T11* was issued to the fleet as an operational weapon only one submarine appears to have received these weapons and none were fired.

An alternative to the "*amsel*" system was the *Pfau* (= peacock) weapon homing system.

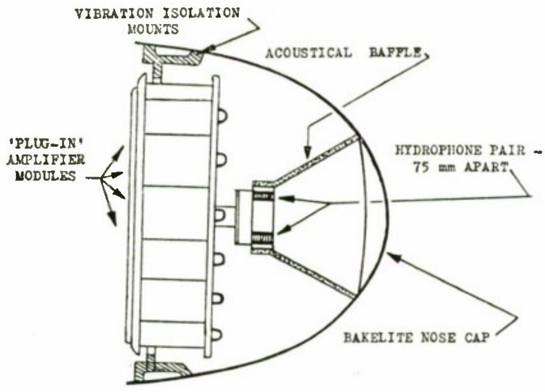

FIG. 33. Homing Head of " PFAU ".

Development started in the mid-nineteen thirties and by the outbreak of war test models were being run. The system was based on phase detection rather than amplitude comparison. Hydrophones, set back behind a "funnel" as shown in Fig. 33, fed their outputs into a phase detection amplifier and the weapon was steered towards the source of noise. The advantages of this system were:

(a) A wide frequency range (compared with the narrow band of the amplitude comparison system) which gave a measure of protection against noise makers.
(b) A wide bearing range available for searching.
(c) Instantaneous indication of target bearing allowing quick response by means of proportional steering systems.
(d) Simple insertion of lead angle homing enabling the weapon to follow an interception course rather than the less efficient pursuit course to the target.

The work suffered a hiatus from 1939 to 1941, along with many other projects because of the German conviction that the war would be of short duration. In 1942 the project was again being pursued under the enthusiastic guidance of the *Pfau* inventor, Ob-Ing Schaper, but was soon abandoned because the requirement for *Pfau* settled only on air-dropped weapons (such as the L5) and the nose cap was unable to withstand the shock of water impact.

Attempts to circumvent the *FOXER* decoy led to a design study for a torpedo homing on very low frequency radiated noise. Such noise cannot be generated efficiently by small towed decoys. Frequencies below about 50 cycles per second were rejected because the noise level varied very considerably from ship to ship—the noise being entirely due to rotating machinery and its out-of-balance characteristics. The frequency range eventually chosen was from 50 to 100 c.p.s. and an experimental weapon code-named *TAUBE* (= Dove) was tested but soon abandoned, largely on account of the high self-noise level and resultant poor acquisition range.

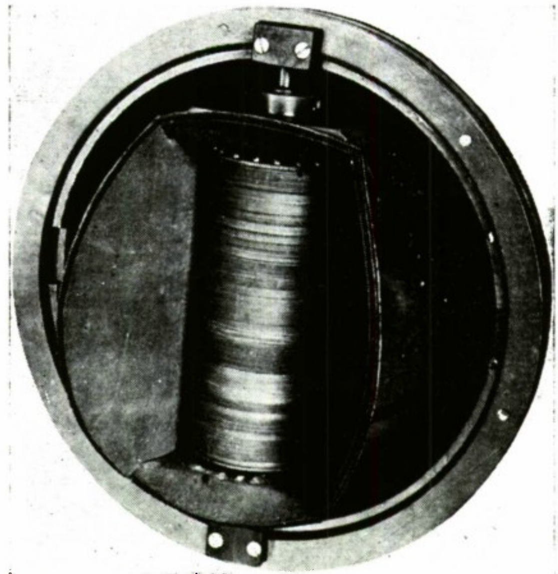

FIG. 34. Scanning Hydrophone from German " LERCHE " Torpedo (1944).

Another ingenious weapon was *LERCHE* (= lark). A passive hydrophone mounted in the nose was driven in a nodding action by a small electric motor, Fig. 34, and the output of the hydrophone was amplified and fed down a trailing wire to an operator in the firing submarine. By an ingenious identification system the operator could hear the modulations on the output of the 35 kc/s magnetostriction transducer together with a series of tones indicating the orientation of the transducer system. The operator could distinguish between the noise of a decoy and the noise of a ship's propellers on account of the "beats" in the latter at the ship's shaft rate. The operator could direct the torpedo to the ship by means of signals fed down the same wire as the acoustic signals. *LERCHE* was fitted experimentally in one submarine but not brought into general use by the end of hostilities. Much of the hardware of this weapon system was captured by the Soviet Union at the end of the war.

Active, *i.e.* pinging, weapons were initially considered impracticable by the Germans but in 1942 an experimental system, named *BOJE* (= buoy), was built to confound the experts. Although the acquisition ranges were generally less than for passive weapons the active system had certain advantages particularly in the presence of noisemakers and against slow or stationary targets.

Although *BOJE* never reached service it stimulated an enormous quantity of research into reverberation; this being of considerable importance to the success of active homing systems. Indeed, the Germans carried out much basic research on the radiated noise of ships and torpedoes and its directional properties. Their research on the noise of propellers, carried out both at sea and in water tunnels at Gotenhafen, and the effects of sea surface reflection of propeller noise to the homing system are, even today, sufficiently relevent to forbid detailed description here.

The successor to *BOJE* was *GEIER* (= Vulture) which had an active acquisition range of 280 yards. The transducer was pendulously mounted to stabilise the variation of reverberation with time from transmission. Two receiver amplifiers were used, these being a time varied gain type to follow the decay of the reverberation and the second was an A.G.C. type to compensate for variations from day to day due to sea state changes. As a result of experience with *GEIER 1* the *GEIER 2* was produced. The listening hydrophone operated over two different bandwidths. The self-noise was different in the two channels but the echo was the same level. Thus, by appropriate amplification and subtraction the self-noise was effectively greatly reduced giving a much improved signal to noise ratio. Another improvement incorporated in *GEIER 2* was the facility for " preferred side " homing in which the weapon only responds to echoes from a certain pre-determined side.

The first pre-production *GEIER* weapons appeared in March 1944 and the *GEIER 2* started test running in the Autumn of 1944. They reached the fleet as operational weapons only a few months before the end of the war.

In conclusion, I will briefly describe some experimental homing weapons that never reached the production stage. *IBIS* (= Ibex) used acoustic echoes from a ship's wake to weave along the wake to the ship. Pings were transmitted normal to the weapon axis and the torpedo steered towards the echo to give a weaving course as shown in Fig. 35. The idea was tested but dropped in 1944 in favour of the *GEIER*. *FASEN* (= Pheasant), like

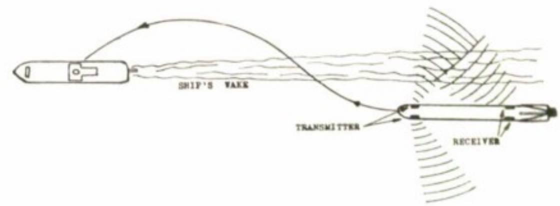

FIG. 35. IBIS Wake Following Procedure.

IBIS detected the echoes received from a ship's wake but having entered the wake the weapon went into a pre-set pattern running procedure. This system was also dropped in favour of *GEIER*. *MARCHEN* (= Fairy tale ! !) was a magnetic homing weapon which achieved acquistion ranges onto large non-degaussed ships of several hundred yards but it was cancelled on account of the variability of ship magnetic fields with position on the Earth's surface. Finally we note the wake weaver devised by Professor Ackermann at the Danzig Technical College. The presence of the wake was detected by its turbulence and this in turn was detected by two pressure tap points near the nose and tail. The turbulence effects were too small to enable a reliable indication of the wake to be given. (It is interesting to note that a similar system was devised in Britain over forty years earlier !)

The Germans developed or studied over fifty types of torpedo including the famous peroxide types and the less well known wireless controlled weapons. They also tested a flat torpedo propelled by a flapping fin and the British revived the flywheel weapon. All of these and more will be introduced in the next of these articles.

Part 4

Abstract

The continuing development of American and British homing torpedoes is described over the period of World War II followed by the important propulsion improvements such as the German " Ingolin " weapons as well as the bizarre " flapping fin " and flywheel torpedoes.

The post-war development of torpedoes, both in Britain and the U.S.A. is described. This includes the 500 knot ' flying torpedoes ' as well as less fabulous weapons such as the ill-fated PENTANE and FANCY projects. It is shown that the British torpedo programme since 1945 has produced three service weapons out of at least nineteen projected, and in many cases experimentally tested, designs.

American Homing Torpedo Developments 1942 - 1947

We saw in the previous part of this history that the German scientists had started work on homing torpedoes in the mid-1930s and produced in 1943 a weapon with a hit rate claimed at 53%. The success of this work was due to years of hard research into the nature of ships' noise, its transmission through the ocean as a function of sea conditions and the problems of detecting noise at a torpedo. The American effort was less successful, partially on account of the lack of a suitable torpedo and partially because of delay in obtaining the vital basic acoustic data upon which a successful homing weapon depends. The first American homing weapon was built very largely on the basis of British acoustic investigations which had started in the late 1930s.

Several projects were started in the United States around 1941 with the intention of producing various homing weapons. Project NO-94 was started to produce a 12 knot anti-submarine torpedo with passive homing in three dimensions. This speed was considered adequate to catch any submerged submarine at that time. The outcome of co-operative work

TABLE 11. Summary of German Electric and Homing Weapons, World War II

Weapon	*Code-name*	*W*	*V*	*R*	*Remarks*
T 2	—	3,540	30	5,470	*First operational electric weapon.
T 3	—	3,540	30	5,470	*T 2 fitted with influence fuze.
T 3a	—	3,870	30	8,200	*New battery fitted.
T 3b	—	2,970	18½	4,390	*Propulsive part of 'Marder'.
T 3c	—	2,950	18½	4,390	*Fired from midget submarines.
T 3d	Dackel	4,885	9	62,300	*Pattern runner. 36 ft. long.
T 3e	Kreuzotter	2,960	20	8,200?	*Used by Molch and Seehund.
T 4	Falke	3,080	20	8,200	*First passive homer.
T 5	Zaunkönig 1	3,300	25	6,230	*Major homing weapon of the war.
T 5a	—	?	22	8,750	*Used by S-boats.
T 5b	—	?	22	8,750	*Used by submarines.
T 6	—	3,870	30	8,200	†T 3a with improved warhead.
T 10	Spinne	3,570	30	3,280	*Wire controlled from coast.
T 11	Zaunkönig 2	3,300	24	6,240	†Improved T 5.
T 12	—	2,780	30	3,280	†18 ft. long—intended for small submarines.
—	Lerche	?	?	6,000	†Operator controlled/passive homer.
G7p	—	?	30	10,000	Proposed Mg/carbon and Zn/Pb batteries.
	Geier 1, 2	?	?	?	†Active homer. Geier 3 planned.
F5b	Pfau	1,810	24	6,600	†Passive homer based on steam/turbine propulsion. Air-dropped.

Notes: W is weight in lbs.
V is speed in knots.
R is range in yards.

*denotes used in service

†denotes reached experimental stage.

by Harvard University, Bell Telephone Laboratories and General Electric Co., was the Mark 24 mine; called such for security reasons. Although 21 in. diameter the weapon was only 84 in. long. Two homing systems were tested and the version adopted had four hydrophones mounted around the body of the torpedo with simple steering towards the noise source. This Mark 24 entered service in late 1944 only 35 months from conception. Shortly afterwards the Mark 27 entered service as a lengthened version of the Mark 24. These two weapons were the only American homing torpedoes to see active service; their activities being in the Pacific.

Project NO-157 was set up to produce an anti-ship, submarine launched torpedo based on the electric Mark 18, which was the American copy of the German G7e. Three weapons were eventually produced. Extensive noise measurements on both sides of the Atlantic showed that a homing range of 200 yards on a 15 knot destroyer could only be achieved by low speed and noise isolation. (It is interesting to note that the Germans regarded propeller noise as the most troublesome source of " self-noise " whereas the Americans had most trouble with motor and gear noise). The first weapon produced under this project was the Mark 28, basically a Mark 18 with the tail gearing eliminated and four hydrophones mounted on the curved part of the nose. With its single propeller the Mark 28 ran at 20 knots which was not really adequate for dealing with destroyers even though electric propulsion allowed the advantage of trackless (and therefore surprise) attack.

The Mark 29 was soon introduced as a 25 knot weapon; the speed improvement having been achieved by using a contrarotating motor directly driving the propellers. Further noise reduction techniques applied to the original Mark 18 together with improved hydrophones now allowed an acquisition range of 200 yards to be obtained at 28 knots and this new version was numbered the Mark 31. Meanwhile, experiments using the Mark 20 straight running torpedo showed that it was possible, by careful positioning of the hydrophones, to achieve the requisite homing range at no less than 39 knots. The homing version of the Mark 20 came into service in October 1945, like all but two of the United States Navy homing weapons, too late for war service.

Project NO-149 was instigated to develop aircraft homing torpedoes. The turbine driven Mark 13 was used as a test vehicle but it was soon found that the turbine was very noisy at ultrasonic homing frequencies. As a consequence the work was due for cancellation in the Spring of 1944 and a " last ditch " effort was made to reduce the noise. Neoprene gaskets and rubber mounts were extensively used with the result that adequate homing performance was achieved at the running speed of 33 knots. Designated the Mark 21, the weapon performed well in homing but failed to achieve many hits. This was found to be due to the poor manoeuvreability in final attack imposed by the shroud ring on the tail; this being used to stabilize the weapon for water entry. Although this problem was overcome success was not achieved until after the war.

TABLE 12. U.S. Homing Weapons Developed 1941 - 1946

Project	*Basic weapon*	*Final weapon*	*Speed*	*Remarks*
NO-94	—	Mk 24	12 kn	A/Sub passive
	Mk 24	Mk 27	12 kn	Improved Mk 24
NO-157	Mk 18	Mk 28	20 kn	A/Ship passive
	Mk 18	Mk 29	25 kn	A/Ship passive
	Mk 18	Mk 31	28 kn	A/Ship passive
	Mk 20	Mk 20	37 kn	A/Ship passive
NO-149	Mk 13	Mk 21	33 kn	Aircraft dropped, A/Ship passive
NO-181	Mk 24	Mk 32	12 kn	Active version of Mk 24
	Mk 18	Mk 18	29 kn	Active Mk 18. Untested

Project NO-181 examined active (*i.e.* echo ranging) weapons. The only successful weapon was the Mark 32, an active homing version of the Mark 24 mine. This weapon was the first U.S. Navy lightweight active homing torpedo being " only " 1,200 lbs. in weight. An active homing version of the submarine launched Mk. 18 was considered but remained a drawing board dream.

Table 12 summarises the American homing weapons planned during the last war.

British Homing Torpedo Research in World War II

British work on homing weapons started before the war as a joint effort between the establishments at Greenock and Fairlie with measurements of ships' noise and torpedo self-noise. It was concluded that useful detection ranges would only be obtained with weapon speeds below about 20 knots. (Remember that German weapons performed well at 25 knots but had the advantage of electric propulsion). There was no naval requirement at that time for such a slow weapon and further work was stopped; the results of the work being sent to the U.S.A.

During 1942 work was re-started on an active air-dropped torpedo project code-named *BOWLER*. The probability of an aircraft being shot down was much reduced by flying along the line of the ship but the chance of achieving a torpedo hit was correspondingly reduced. Bowler was intended to overcome this disadvantage by giving the weapon a homing capability from fine aspect attacks.

Quartz crystal transmitting hydrophones on each side of the weapon emitted pulses of 26·7 kc/s noise at right angles to the weapon axis. On receipt of an echo from a ship the weapon turned towards the echo on a controlled turn, which should have resulted in a broadside impact. Measurement showed that echoes would be detected at ranges up to about 100 yards (corresponding to a signal to noise ratio of 12 to 20 db according to sea conditions). This effectively gave a ship an extra 200 yards width for attacks from ahead; attacks from aft being impracticable on account of false detections from the ship's wake.

Systems studies showed that only shots from within 20° of the bow stood a good chance of hitting and the weapon could be countered by setting off charges in the water to give premature turning. With salvo fire the explosion of one weapon caused premature turning of the second. Because of these difficulties the project was cancelled. It is as a rule better to have a poor weapon rather than no weapon and any homing capability would not, it seems, detract from the usefulness of the basic weapon system (the 18 in. Mark 17 running at 40 knots). It is difficult to understand the reasons for cancelling this project at a time when aircraft were suffering heavy losses in torpedo attacks.

Be that as it may, Bowler was dropped and a new project got under way under the codename *TRUMPER*. Based on the 21 in. Marks 8 and 9 Trumper was an active weapon built in collaboration with the General Electric Co., Wembley. The design was settled in 1943 on the basis of acoustic data obtained in support of Bowler and in the Winter of 1943 a trial was carried out against a submarine. Initially the target bearing was found by phase comparison but this was dropped in favour of amplitude comparison. The quartz crystal transmitter and the mosaic of receiver crystals were mounted inside an oil-filled dome fitted onto a special flattened Mk. 8 nose. The two stacks of crystals were paired to give a single broad beam with a beamwidth of about 60°. " On-off " homing was used; that is say, the target was kept on the edge of the beam to give a lead angle of about 30°. This gave some measure of protection from towed countermeasures and the ship's wake, the preferred side being capable of selection according to the angle of attack. When the range of the target had fallen to 170 yards the weapon made a 40° turn to achieve a hit.

TRUMPER was undergoing sea trials when the war finished and as a result the British failed by only a few months to get a homing torpedo into service. *TRUMPER* was postponed and the " Trumperised " Mark 8 and Mark 9 weapons, together with an electric Mark 11 which had been fitted with a homing head, were used for noise research.

The British had started development of an active homing anti-submarine torpedo in 1942. Wing Commander St. John and two other officers at Technical Training Command, Reading worked out various systems and started testing them in their off-duty hours. When a reasonably satisfactory electronic circuit had been devised for steering a weapon towards a target, Squadron Leader Robertson (later Chief Scientist at T.E.E.) joined the team to design the mechanical hardware. Phase comparison was to have been used to set the gyro course in azimuth and depth. By this time the Bowler active torpedo system was being developed and, because of the clear similarities in the programmes, the two projects had their expertise pooled under the code-name *JOKER*.

Considerable trouble was experienced with reverberation, self-noise and water entry shock for it was at that time proposed to use the standard 18 in. Mk. 15 torpedo as the body of the new weapon. In 1943 the situation was reviewed and the Joker projects were freshly divided into *DEALER* and *TRUMPER*; the former to be a passive surface-launched weapon and the latter, as we have seen, to be an active weapon.

Nearly all the design work was carried out at R.A.F. Halton and later at Titchfield. The first prototypes were produced by the R.A.F. but the production run of 100 weapons was undertaken at R.N.T.F. early in 1945. These weapons were scrapped soon after production and none were used in action.

The *DEALER* was one of the most curious weapons to emerge during the war. On changing to passive homing the weapon was redesigned to enable it to be dropped from an aircraft with parachute retardation. The weapon, unlike all its contemporaries, had no control surfaces for steering. Two propellers were set in tandem on each side of a fixed rudder, each with its own independently energised motor. Steering in azimuth was achieved by varying the relative voltage. Depth control was by motoring the main battery to-and-fro, thus altering the position of the centre of gravity. The hull was tapered slightly from nose to tail.

The *DEALER* weapons led at the end of the war to Dealer B, an 18 in. passive torpedo of conventional appearance, and Bidder which started as a passive 18 in. anti-submarine weapon but finished as the 21 in. passive Mk. 20. The story of these weapons will be examined later. We will continue now with propulsion work.

Torpedo Propulsion 1939 - 1945

Britain, the inventor of the enriched air torpedo which was so extensively copied by the Japanese, reverted on the outbreak of war to natural air and the main wartime thermal torpedo is still in service today. This situation is not for want of innovation by British scientists as I hope to demonstrate in the following pages. The blame, if blame there be, lies with the exigencies of war.

The " workhorses " of the British war effort were the 21 in. Mk. 8 and Mk. 9 and 18 in. Mk. 12 and 15 torpedoes, all of which worked on the Burner cycle engine described previously. The main research work in Britain in propulsion fields was aimed towards increasing the speed of torpedoes because this reduced the aiming errors and their effects. The burden carried by torpedo designers is the law whereby the power required by a weapon increases approximately as the cube of the speed. Thus a speed increase from 45 to 60 knots requires a power output increase of about 240%. Even so it was the aim of designers to achieve 60 knots.

The pre-war 21 in. Mk. 8 achieved 40 knots at a rating of 230 b.h.p. and this was soon uprated to 45 knots at 322 b.h.p. The longer ship launched Mk. 9 required 360 b.h.p. to achieve the same speed. In 1939 a new engine was built[37] which delivered 817 b.h.p. At nearly two b.h.p./lb. this was twice the corresponding figure for the Bliss turbine used to power United States torpedoes. As shown in Fig. 36, the engine was two radial engines " Siamesed " to give an eight-cylinder engine with four combustion pots. Although this weapon was expected to produce 60 knots in a Mark 8 shell, it was never brought into service and experiments on the engine and similar types continued for many years even after the war was over.

Only minor improvements were made to engines in Britain during the war; the only

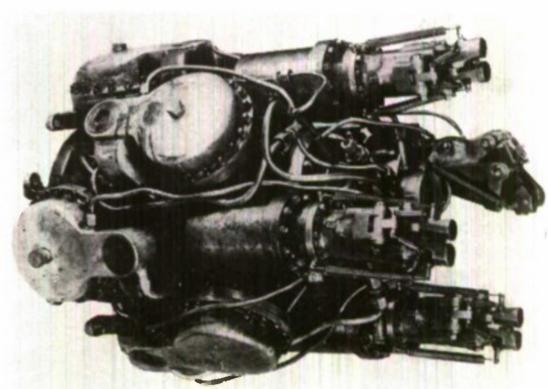

FIG. 36. Eight-Cylinder British experimental engine (1939).

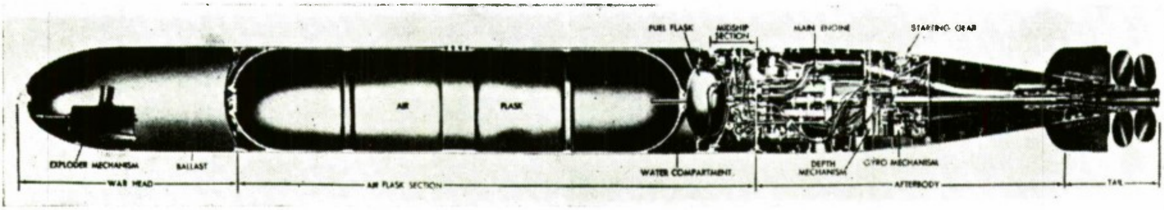

FIG. 37. U.S. Mark 14 weapon.

significant advance being the introduction of the 21 in. Mk. 11 electric torpedo described previously.

Research on fuels and oxidants was active during the war with many new systems under investigation but ultimately not leading to a service weapon. The generation of hot gases for a standard engine by the burning of a solid mono-fuel (*i.e.* a mixture of fuel and oxidant in a single block as in rocket systems) was investigated from 1942 until just after the end of the war. The object of these investigations[33] was three-fold, namely to eliminate the expensive air vessel, to save weight in general and to use a simple, cheap engine of the old " wet-heater " type.

The solid charge, which was based on ammonium nitrate and solid organic fuel, was manufactured in a sealed container for direct insertion into a torpedo. The temperature and pressure of the gas were controlled by the composition and shape of the solid charge. The gases so generated were fed directly to the inlet valves of the engine, a wet-heater from a 21 in. Mark V. The first propellent tested at Greenock in January 1945 was ammonium nitrate and gunidine nitrate with five to 10% ammonium dichromate catalyst. The end product was 65% steam, 16% nitrogen, 1% carbon dioxide and 9% each of nitrous oxide and nitrogen dioxide. Ammonium oxalate was injected to cut down engine corrosion.

This work on solid propellents was run down and stopped soon after the first successes had been achieved through general lack of support. It is interesting to note that the U.S. Mk. 46/0 torpedo which is at present the standard lightweight weapon in the United States uses a solid charge propulsion system as devised, but never used, by the British.

Moving on towards the bizarre we find experimental work at Greenock in 1942 directed towards a jet propelled torpedo[35]. The only advantage of jet propulsion evident to the author is the lack of engine and other moving parts. The propulsive performance is very poor. A 21 in. Mark V torpedo was disembowelled and four combustion pots were fitted in the engine space followed by a divergent nozzle in the after-body in place of the propellers. The torpedo ran well and was easily controlled but only achieved a speed of 24 knots to a range of 800 yards. This was not too depressing for the builders because the weapon was only put together from spare parts; with a proper design it was estimated that a performance equal to that of the contemporary electric weapons would be obtained. There was not the requirement at that time for low performance weapons, even if of simple construction. The jet torpedo was never seen again.

Moving even further towards fantasy we find a proposal[34] in 1941 to revive the idea of a flywheel driven air-dropped torpedo. The advantage of such a weapon was intended to be its cheapness and simplicity of manufacture but when compared with the then standard aircraft torpedo, the 18 in. Mk. XII, it was found that the skilled labour required was nearly 7,000 man-hours and the unit cost was about £950. This latter was £600 less than the Mk. XII but the surprisingly high labour requirement killed the weapon.

The design for the weapon included two contrarotating wheels on an axis parallel to that of the weapon. This neutralised the overall gyroscopic forces (but not the forces on the axis of each wheel) and the wheels drove the propellers through a three-speed gear box and constant torque converter. The maximum stress allowed in the wheels was set to 55 tons which, for an 18 in. diameter weapon corresponded to a speed of 24,000 r.p.m. maximum. This allowed $1{\cdot}25 \times 10^6$ ft./lbs. of energy to be stored for every inch length of wheels (allowing that only 50% of the potential energy is recoverable). With wheels of length 2·3 in. each (thus 130 lbs. each in weight) the available energy would have given a performance of 27 knots and a range of 1,800 yards. This was approximately half the performance of the Mk. XII weapon.

A further disadvantage of this weapon would have been the need to spin the wheels to a top speed before aircraft take-off and maintain the wheels at speed whilst in flight. There are obvious difficulties here. The very low dropping height required also caused much criticism.

The system was designed to meet the above speed and range requirements and was not therefore an optimum. With present day materials and allowing the weight of wheels to be one third of the weapon overall weight (this corresponds approximately to the proportionate weight of air vessel and engine in a burner cycle weapon) we find that a flywheel driven 18 in. weapon of the size of the Mk. XII should now be capable of 27 knots to a range of about 6,000 yards. This is about 50% greater than the Mk. XII and slightly greater than the post-war French *L*3 electric anti-submarine torpedo; this latter having the advantage of a greater diameter (550 mm) and hence greater theoretical output.

The propeller, being a source of noise when cavitating, was given considerable attention during the war. The Germans made extensive measurements of the noise of propeller cavitation as it varied with depth and angular position about the weapon. Water tunnel investigations were also made into the nature by propeller noise. Two attempts were made to circumvent these problems by eliminating the propeller altogether. We have already met the jet torpedo whose objective was a simple means of propulsion rather than noise reduction. The British revived the " umbrella " means of propulsion whereby the weapon is propelled forwards by a folding pair of vanes oscillating back and forth in the axis of the torpedo[36]. On the thrust stroke the vanes open and push the water aft causing a forward reaction on the weapon whilst on the return stroke the vanes collapse and offer little resistance to flow. The difficulty with this system is not perhaps the operation of the vanes but the generation of a back and forth motion by means of a simple engine. The device was never tested.

Similar thoughts in Germany had resulted in propulsion by a flapping fin after the fashion of a fish. Initially a simple flapping vane was fitted to a standard *G*7e and it was found that an efficiency of about 60% was achieved. Further experiments showed that a fixed fin behind the flapping fin increased the efficiency to the same value as a conventional propeller.

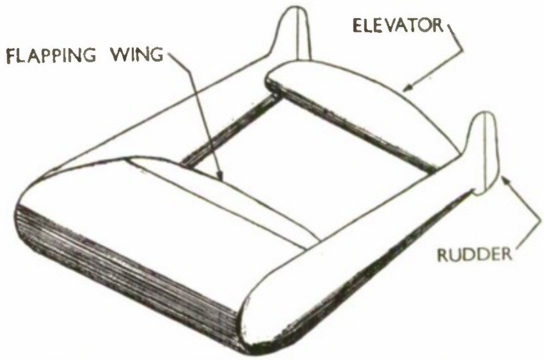

FIG. 38. German " Flapping Wing " torpedo (1944).

Eventually the weapon sketched in Figure[38] was built and tested. The unconventional appearance may cause humourous comments from some readers but I must point out that this device had many advantages over conventionally-shaped weapons and further development was only halted by the war ending before trials were complete.

The flapping wing weapon was driven by the same power plant as the *G*7e torpedo. Cavitation noise was negligible and the device was altogether much quieter than conventional torpedoes. Stability was excellent in all planes. The considerable lift obtained with only moderate angles of incidence enabled the weapon to be very dense (compared with the stability requirement for conventional torpedoes to be nearly unity specific gravity) and as a result the overall propulsive efficiency in terms of energy required to transport a given weight of explosive was somewhat better than many production weapons. The obvious disadvantage of the weapon is the problem of launching from submarines although some type of slide launcher could be used from ships.

One of the outstanding developments of the last war was the application of hydrogen peroxide to propulsion and we will now look at the German developments in the torpedo field.

German Peroxide Weapons of World War II

Before the start of World War II the Germans had been experimenting extensively with oxygen carriers to eliminate as far as possible the heavy air vessel and provide trackless performance, this latter becoming vital later in the war. By 1939, the search for oxygen carriers was chaotic at T.V.A. (Torpedo Experimental Establishment) and Herr Lawitska was then put in charge. A systematic investigation of likely systems was initiated.

The use of pure high pressure oxygen, as used by the Japanese, was rejected because of the starting problems which sometimes resulted in explosions (the Japanese avoided this however by starting ignition with air and increasing the enrichment over a 15 second period). Several other high energy systems were tested of which a selection were:

(a) Hydrogen and oxygen. This was abandoned on account of the rapid diffusion loss of the high pressure hydrogen (25% gas loss from a pressure vessel in only three days).

(b) Ammonia and oxygen. Liquid ammonia gave promising results but the system was given up in 1938 because of the track formed by dissociation of excess ammonia.

(c) Carbon dioxide, fuel and oxygen. The carbon dioxide was proposed as diluent but the work was stopped because of the risk of CO_2 leakage into the living space of a submarine.

(d) Magnesium (or aluminium) and oxygen. Very energetic but too difficult to control for torpedo applications.

Ultimately the hydrogen peroxide system was developed.

The development of the "Ingolin" or hydrogen peroxide torpedoes was started in 1930 by Professor H. Walter. Altogether no less than 16 types of these weapons were developed but only three were approaching operational status by the end of the war. The first successful application outside the torpedo field was in jet propulsion devices. The peroxide was decomposed with sodium or calcium permanganate according to the reaction:

$$MnO_4 + 2H_2O_2 \rightarrow MnO_2 + 2H_2O + 2O_2$$

and

$$2H_2O_2 \rightarrow 2H_20 + O_2$$

where the second reaction is catalysed by the MnO_2.

The finely divided particles of MnO_2 are objectionable in a turbine and as a result the catalytic decomposition using "Helman" was developed. A typical weapon of German peroxide technology was the *STEINWAL* which will now be described in detail.

The *STEINWAL* was a four-fluid weapon if the liquid "Helman" is counted as a working fluid. "Helman" consisted of 80% hydrazine

TABLE 13. Comparison of certain World War II topedoes

	U.S.	*U.K.*	*German*		
	Mk 14-3	Mk 8	*G7a*	*Steinbutt*	*Steinwal*
Range, yds	4,500	5,000	6,600	8,750	24,000
Speed, knots	46	45·5	44	45	45
Engine	Turbine	B-cycle	Radial	Turbine	Turbine
Fuel	Alcohol	Paraffin	Decalin	Decalin	Decalin
Fuel wt, lbs.	28	30	36	37	110
Oxidant	Air	Air	Air	H_2O_2	H_2O_2
Weight of oxidant, lbs.	256	241	350	284	814
Diluent	H_2O	—	H_2O	H_2O	Sea water
Diluent wt, lbs.	83	—	125	378	—
Total weight of expendables (lbs.)	367	271	511	758	1,029
Expendables used (lbs./h.p.hr.)	19·5	9·0	18·7	17·7	8·5

hydrate, 20% ethyl alcohol and 0·5 gram per litre of potassium copper cyanate, $K_2Cu(CN)_3$; this latter being added to assist ignition. The fuel was Decalin (decahydronaphthalene). Combustion was started by mixing the Helman, fuel and hydrogen peroxide in the combustion pot. Once fired, the flow of helman was cut off and the fuel and peroxide burnt continuously at a temperature of about 2,300°. Because of the difficulty of storing Helman it was arranged that the copper salt was added to the catalyst just prior to mixing with the peroxide. The Helman and fuel had to be admitted to the combustion pot slightly before the peroxide. If the peroxide arrived first it decomposed explosively into water and oxygen giving up about 660 calories per lb. which is sufficient to convert the water to steam. A complex system of cam-operated valves ensured that the fluids were mixed in the appropriate fashion. Table 13 below summarises the characteristics of two German peroxide weapons and compares them with the standard wartime British Mk. 8 torpedo.

It should be noted that the British B-cycle engine is far more efficient than all other weapons with the exception of the *STEINWAL*. The relatively low range of the Mk. 8 is due to the low weight of oxygen carried compared with the torpedo weight. Such is the advantage of a dense low pressure oxidant such as hydrogen peroxide.

It will be noted from the table that the Germans changed from radial reciprocating engines to turbines during the war. The reason was primarily to eliminate oil from the exhaust and render the weapons completely trackless. Many types of turbine were tested and the finest was that fitted to the *STEINWAL*. It was rated at 500 h.p. and had a speed of 30,000 r.p.m. and was actually machined from a solid steel disc by a machine developed at the firm of Askania, Berlin. Another revolutionary feature was a cardan gear on the driving shaft which, with an internally toothed flywheel ring, revolved in the opposite direction thus preventing initial roll on firing[30]. The exhaust, such as it was, bubbled out through a perforated ring around the engine compartment. The bubbles quickly dissolved. One claim for this type of exhaust was a reduction of radiated noise from the engine due to the bubble screen.

The long range of the Steinwal was developed solely for the pattern running capability. Complex patterns could be run through a con-

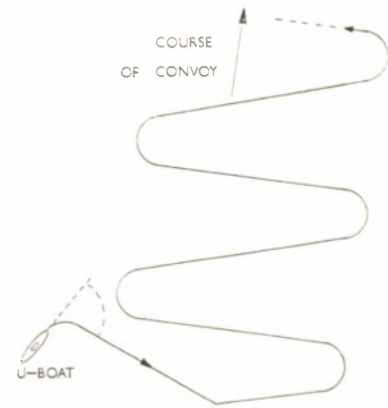

FIG. 39. German "LUT" pattern running.

voy giving little chance of avoidance because of the numerous and devious course changes.

A special gyro, the *LUT*, was made to allow the weapon to follow the programmed path. Fig. 39 shows a typical *LUT* track.

The Germans experimented with peroxide weapons using the jet idea and claim to have achieved 1,310 yards range and 45 knots. Table 14 summarises the experimental weapons of the last war together with a few operational types.

The popular impression that peroxide torpedoes were the major objects of German wartime research tends to over-shadow the fact that a large proportion of scientists favoured pure oxygen rather than hydrogen peroxide, after the manner of the Japanese. Teams of scientists travelled to Germany from Japan by U-boat to advise the Germans. However, by the end of 1943 the oxygen work was falling behind the peroxide developments and the former was cancelled. The oxygen work was based on a closed cycle system whereby the exhaust gases were fed back into the combustion pot to act as diluent; any build-up of pressure being released by exhaustion of the steam and CO_2, the soluable products of combustion. Experiments on this system began in 1930 using a car engine and in 1937 the Junkers Aircraft and Engine Company produced the huge experimental M5 torpedo. Measuring 29·6 in. in diameter and over 36 ft. in length, its engine developed some 600 b.h.p. but the weapon was a failure. Every test model sank on trials and the project was given up.

Tests at the end of the war on the surviving Junkers engines showed that the M5 weapons would have achieved 26,000 yards range at a speed of 40 knots.

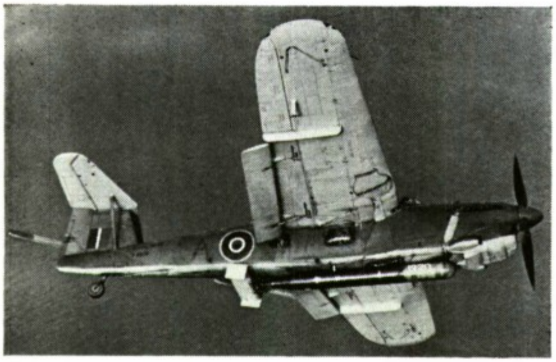

FIG. 40. Barracuda. Note aerodynamic tail on torpedo.
(Courtesy of Imperial War Museum)

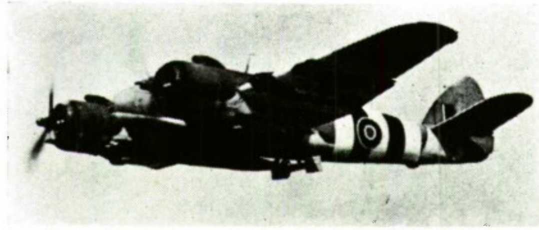

FIG. 41. Bristol Beaufighter Mk. VI.
(Courtesy of Imperial War Museum)

Of all the nations engaged in torpedo development, the Germans showed the greatest inventiveness and, if the war had continued for a further year the Allies would have been threatened by deadly pattern running peroxide weapons and new homing torpedoes. The lessons to be learnt from this programme are summarised as following by the (anonymous) author of B.R. 1972 . . .

> " The German torpedo development was separated from torpedo production at a high level in the O.K.M. (Naval High Command) though both were within the torpedo branch. The development side had their own facilities for experiment, and for experimental manufacture on a large scale, which were entirely independent of factories manufacturing weapons in bulk. In times of peace there is a tendency to combine the two on the grounds of economy, but if this is done, and especially if they share the same workshops and workpeople, the result in war is disastrous for development, which is inevitably squeezed out by the over-riding claims of production."

> ". . . at first the inventor is the only authority who has the necessary knowledge to deal with the work, and it is most important to establish a technical team to take over as soon as possible, and free the inventor for his proper task of further development."

> ". . . Germany used private firms to develop not only components, but complete torpedoes. Two advantages stem from this policy. Firstly, and most important is the element of competition lacking in a Government establishment. Secondly, the firms bring specialist expertise to bear from fields outside that of torpedoes. The expertise is most important when dealing with production problems."

The failing of the German torpedo programme was the lack of co-operation between the Navy and the Luftwaffe. Independent programmes were being followed at one time and these lacked sufficiently strong supervision to weed out the poor projects. The fact that the Germans tried over 60 different torpedo designs shows clearly the lack of control over experimental work.

Man/Torpedo Combinations in World War II

Several attempts were made during the war to combine the intelligence of a man with the destructive power of a torpedo. Some of these combinations come more truly under the heading of midget submarines. The Japanese Kaiten, for example, was an oxygen 24 in. torpedo propulsion system built into a torpedo-shaped body; the entire device weighing over eight tons. It can be seen from this that the *KAITEN* was more submarine than torpedo. These suicide weapons were built in large numbers towards the end of the war but are credited with only one sinking; a tanker.

German ideas centred around the use of two weapons in tandem; one carrying the man and propelling the second weapon to the target area. A *T3b*, carrying a man sitting astride the forward battery section and behind a small cockpit, was strapped to a standard electric *G7e*. The tandem system ran slowly with the " pilot's " head bobbing above water to see the way ahead. When within range of a target the offensive weapon was released and the man returned to base or was later picked out of the water. This system was named *MARDER*.

The Italians similarly developed man-controlled torpedoes called *PIGS* and caused havoc with three of them in Alexandria harbour.

Fuze Developments

Before leaving the World War II period we will consider the German *TZ5* pistol. Up to the introduction of the homing torpedo the impact pistol was placed at the weapon nose; often, as in the German examples as a set of whiskers on the nose. The impact of the whiskers set off the warhead. With the nose later reserved for homing transducers the impact pistol became an inertia device set at the rear of the warhead bulkhead. In addition the various magnetic pistols were introduced to provide explosions beneath the keel of a ship rather than on the well-protected side plating.

The failure of these magnetic pistols and their impracticality in rapidly weaving homing weapons resulted in the magnetic influence fuze, or *TZ5* as it was known to the Germans who first fitted it in the *GNAT*. Basically a metal detector, the fuze consisted of two coils, one radiating at a frequency between 50 and 200 c.p.s. The coils were balanced so that no induced field was recorded in the second coil. In the presence of a mass of metal, even if completely lacking magnetic field on its own account, the receiver coil was induced with a current and the warhead detonated. The German influence pistol was made sensitive only to metal above the weapon so that the firing submarine could escape to safety by diving after discharge.

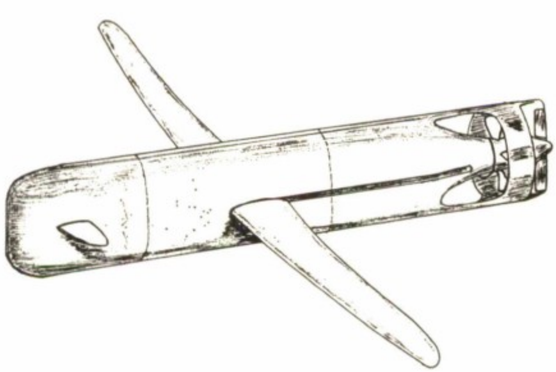

FIG. 42. British flying torpedo (1947).

Both the British and Germans tested optical fuzes which operated on the detection of the shadow of a ship—clearly of use in daylight only—and these operated fairly well but only in experimental tests. The German PiO optical fuze transmitted ultra-violet light towards the surface with a modulation of 1,400 c.p.s. to discriminate against daylight. The transmission direction was chosen to eliminate sea surface reflections. It was found that the U.V. light caused the sea to fluoresce and infra-red light was then used from a 100 watt source. By the end of the war this system had operated well six feet under typical ship targets in experimental firings. This optical fuze was developed because of fears that the magnetic fuzes would be countermined.

Post-War British Developments

At the end of the war the British torpedo experimental work suffered a massive upheaval with the introduction of a programme for the development of new weapons of revolutionary performance. These were the "Z-weapons" of which five main types emerged in an advanced design stage with other types abandoned on the way. The five weapons were:

ZONAL—Ship-launched, anti-ship torpedo fired from tube and then skimming the sea at low altitude at about 500 knots propelled by its ducted propellers and supported on wings. On entering the water, beyond anti-aircraft gunfire range, the wings folded away. The underwater path was at 60 knots with active homing.

ZOSTER—Aircraft-launched version of ZONAL.

ZOMBI—Submarine-launched 30 in. diameter weapon capable of homing to a depth of 1,000 ft.

ZETA—Anti-submarine air-launched weapon.

DEWLAP—M.T.B. weapon, 21 in. diameter.

Figure 42 shows a sketch of one form of *ZONAL* with its elliptical cross-section, chisel nose and ducted propellers. The non-circular cross-section was chosen to strengthen the hull for high speed water entry as well as providing a convenient volume into which the large engine could fit. The shape also allowed a large wing area to be accommodated for a given wing span. As noted above, *ZONAL* was to have been driven in air and water by the same propellers, only a gear change on water entry being deemed necessary.

Much hydrodynamic research was carried out on body forms at the Glen Fruin water tank, the wind tunnel of the Blackburn Aircraft Co., and the cavitation tunnel at Haslar. The great bulk of the work was however on paper. Seemingly endless designs and redesigns were carried out to fit the fictitious components into a given hull. This is acceptable if the components of a new weapon are all developed, at least to a post-feasibility stage, but with the Z-weapons many of the components were pure illusions; component size was sometimes greatly under-estimated (the radio altimeter would have hard pressed even modern technology to fit the space allocated) and other components were so poorly investigated that they would not have worked satisfactorily had they been built. It is possible, with hindsight, to calculate the homing range of the Zonal and Zoster weapons and this is not greater than 150 yards. This is far too small to be of use and it would have required at least a decade to improve on this figure. Thus we see that the Z-weapon projects were, in a sense, developed in reverse. The research and development were largely omitted or held over whilst the weapons were designed in great detail.

As a drawing office exercise the Z-weapons no doubt resulted in the training of many students recently released into civilian life after the war and provided challenging work for the older drawing office staff, but as an exercise in producing weapons the Z-weapon project was almost a complete failure. Robertson, one time Chief Scientist at T.E.E. later wrote that the late 1940's " were devoted expensively to the realms of science fiction ". All was not a failure however. Valuable work was carried out on engine development for the Z-weapons, although even here the work was mostly on paper. Propulsion was to have been by opposed cylinder engines working on pure oxygen and methyl alcohol. For *ZOMBI, ZONAL* and *ZOSTER* a three-cylinder (six-piston) engine was planned to develop 900 b.h.p. Development work on this engine with its hollow crankshafts produced much of value but at what cost in money and manpower !

The Z-weapon programme came to an abrupt halt in about 1949. Life had by then become too difficult for aircraft to torpedo ships because of improved anti-aircraft weapons. We shall no longer find the torpedo-plane carrying out the role that it so successfully pursued during the Second World War.

Fortunately, the weapon development programme at T.E.E. had not quite been carried out to the exclusion of other work than Z-weapons following the war . The homing torpedo programme was still pursuing the *DEALER* and *BIDDER* projects touched upon earlier.

At this time the war-time *DEALER* with its tandem propellers was renamed the *BIDDER A*, the original 18 in. *BIDDER* became a 21 in. weapon, later to be the Mk. 20, and a new 18 in. air dropped weapon was started under the code-name *DEALER B*.

Squadron Leader Robertson who had developed the original wartime *DEALER* joined T.E.E. as a civilian and initiated the new *DEALER B* programme to make an 18 in. passive weapon as an improved version of the original Dealer. The Dealer B evolved as an eight finned, conventionally twin screwed, passive homer[38].

DEALER B became the 18in. Mk. 30 and it proved to be very successful. Trials against submarine targets in 1953 showed that a high hit rate was achieved and the Captain of H.M.S. *Vernon* commented that a new era had dawned in torpedo warfare—the submerged submarine was no longer secure ! The provisional release certificate for fleet issue was given in June 1954 . This date is notable because it marked the start of the anti-submarine torpedo in Britain—a role which has become increasingly more important.

Certain improvements to the 18 in. Mk. 30 were planned for the Mod. 1 version which, it was estimated, would give the weapon a hit probability better than any weapon then available in the world. Despite the fact that several weapons were built and tested, the Naval Staff cancelled the requirement and used the money allocated instead to buy American active homing Mk. 43 weapons. Trials with this weapon had shown a hit rate some four times *worse* than the Mk. 30 in its original form. Some 50 Mk. 43 weapons were obtained and a contract was placed with the Plessey Company for anglicisation in 1956. These weapons were intended to " stop a gap " until the arrival of the American Mk. 44 in Britain, but this did not appear for another 10 years.

Although an informal decision appears to have been made in the mid-1950's to give up producing new lightweight torpedoes in Britain and rely on buying American weapons, never-the-less a proposal was submitted in 1956 for a new 25-knot active/passive helicopter-borne weapon of 14 in. diameter. The project was pursued and by 1957 a prototype passive weapon was running using the basic Mk. 30 motor with a new homing system. The active electronics were bench-tested and ready to be fitted but in 1957 a Staff decision was made to stop all air-dropped weapons and concentrate on submarine and ship torpedoes. As a result it was abandoned along with a 12 in. weapon developed " unofficially " a year or two earlier code-named *NEGRESS*.

Also abandoned at this time was the ill-starred *PENTANE*, one of the best engineered weapons so far produced in Britain or America. *PENTANE* was born in 1947, following the collapse of the fabulous (literally !) Z-weapon programme. The requirement was set down for an active homing air-dropped weapon to cope with submarines of potentially enormous propulsion improvements likely to be found in the 1950's and beyond. Work was initially concentrated at Teddington and T.E.E. engineers were moved from Greenock.

The weapon was designed to run at 30 knots and be capable of catching high-speed submarines. The carrying aircraft were the *Gannet, Sturgeon, Lancaster, Shackleton* and flying boats. It was not until 1954 that a final design was selected on the basis of extensive research carried out over the preceding six years. By this time however the fixed wing aircraft capable of carrying a 21 in. weapon were being withdrawn from service and the helicopter was being considered as the prime torpedo delivery system. Instead of cancelling the project and starting a new lightweight torpedo, the work was allowed to drop from the top priority that it had enjoyed up to then and it continued until 1958 at which point it was finally cancelled. The cancellation was not, rather unexpectedly, due to lack of a suitable carrier but due to an assessment of the weapon's performance. This showed that the search rate was too slow for the targets then likely to be available[42]. Pentane died therefore because it was too late in development, not initially well matched to the future carriers and not adequately matched in homing performance to targets' capabilities.

Excluding these failings, the weapon itself was well engineered, as Fig. 43 shows from the tail unit alone, and as the first British active torpedo it provided valuable experience for future weapon considerations.

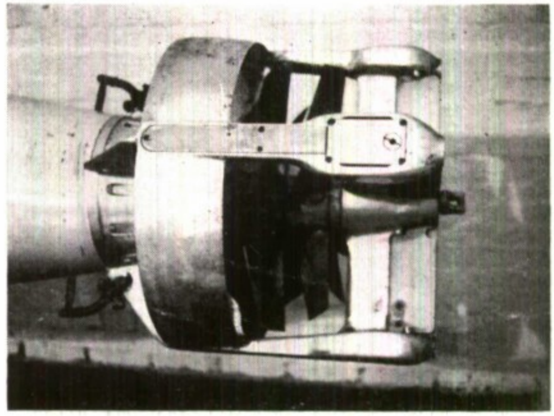

FIG. 43. Pentane tail.

The sad facts of the *PENTANE* affair were

(a) that the potentially very successful Mk. 30 mod 1 was cancelled because of Pentane's top priority and U.S. Mk. 43 weapons were purchased instead,

(b) that other potentially worthwhile projects were held back for the same reason, and

(c) that £1,726,000 were spent on the project; more than the total spent on the only two successful projects by a factor of two.

The initial doubts over the propulsion performance of Pentane gave considerable impetus to the development of silver/zinc batteries and thermal propulsion systems which have proved of great value in recent years.

With the cancellation of Pentane, the Naval Staff decreed that Britain would in future concentrate on ship and submarine-launched weapons. The 21 in. *BIDDER* (Mk. 20) had already entered service as a result of a development programme extending from 1945 and wire-guidance work had also continued. Initially, trials of wire-guidance were carried out by paying captured German wire (from their *SPINNE* weapon) out from Mk. 11 weapons. This work was carried out with the help of Post Office engineers. The work was pursued under the code-name *MACKLE* with Vickers Armstrong playing a large part. In 1956, the contract with industry was terminated; the result being a very complex guidance system applied to Mk. 20 weapons. The system was simplified and improved and renamed *GROG*. This weapon was a lengthened version of the Mk. 20 with a drum of guidance wire carried in the extra length. A dispenser is

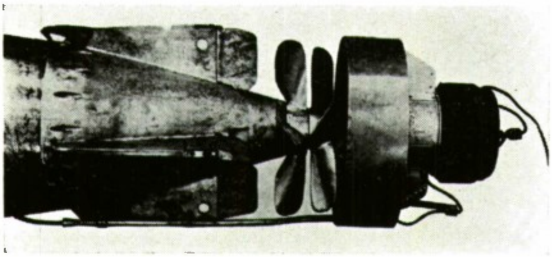

FIG. 44. U.K. Mark 23 wire dispenser.

attached to the weapon's tail as illustrated and this is ejected with the weapon. After launch the dispenser is detached and trails behind the submarine bow regions. The first *GROG* torpedoes became available for trials in 1955 and the first batch of 25 weapons for trial order were started in 1959. Renamed the Mk. 23 torpedo, this weapon has now been in Fleet service since about 1966. It is a sobering thought that the Mk. 23 is basically a wire-guided version of the Mk. 20 whose origins date back to about 1950. Thus our present weapons have histories going back over 20 years.

A large number of projects were embarked upon during the post-war years, most of them of minor importance, but probably the major one of those not considered above was the *FERRY/FANCY* weapon. At the end of the war, the German work on peroxide high performance torpedoes had reached such an advanced stage that the British rebuilt the captured weapons, such as the *STEINBUT*, and tested them. From this experience, work was started on a British long range weapon powered by peroxide and standard fuel. For economical reasons it was decided to modify the standard Mk. 8 weapon to run with hydrogen peroxide. Although, after certain modifications, the Mk. 8 burner cycle engine was made to withstand long running times at full speed, the modifications required in the rest of the torpedo were considerable.

Nearly all the materials used in the Mk. 8 weapon were incompatible with hydrogen peroxide and only after a very great deal of painstaking metallurgical research was an acceptable design obtained. The financial stringences imposed by the priority of Pentane had caused a great deal of extra money to be spent modifying the Mk. 8. A completely new design might well have been cheaper in the long run but would not have solved the problem of what to do with 500 Mk. 8 weapons already in stock!

By 1953, the first peroxide weapons were ready except for their pattern running gyroscopes, and successful runs were made. These weapons were redesignated FANCY S.R. In 1954 several torpedoes were issued to H.M.S. *Maidstone* and over 200 runs were made until the disastrous explosion onboard H.M.S. *Sidon*. The result of the inquiry was to make sure that all surfaces within the torpedo into which hydrogen peroxide could, by human or material failure, be introduced were compatible with the fluid. Further running was marred by an explosion of a torpedo which ran onto a shore of the Arrochar range. This, combined with very stringent new standards for the peroxide vessel, raised considerable problems and in January 1959 the requirement for the *FANCY/FERRY* weapons, or 21 in. Mk. 12, as they had been renamed, was cancelled.

Many projects were pursued in the period up to 1960, many were torpedoes and others were sub-components such as the swashplate engines developed for *PENTANE*. It is not proposed here to detail these projects but the following table sets out the torpedo projects. Of the 19 torpedo and counter torpedo vehicles projected only three have so far reached service. Some projects did not proceed beyond the feasibility stage.

Considering projects between 1950 and 1960 costing more than £150,000 we find that over 70% of the money and 69% of the R. and D. effort were expended on cancelled projects.

Vickers, Armstrong, Ltd., at Weymouth produced 75 Mk. 20 weapons under contract and worked for a while on wire-guidance for the Mk. 23 but, after an unsuccessful private venture with a homing torpedo in the early 1960's, the torpedo department ran down until the Weymouth factory was closed. R.N.T.F. was similarly run down and sold to Plessey Co. in 1970.

U.S. Torpedoes between 1945 and 1970†

Torpedo development during the war in the U.S.A. was so rapid that relatively little development occurred in the immediate post-war period. The Mk. 29 and Mk. 27 weapons produced at the end of the war remained in service until quite recently; indeed they were still on the active list in 1960. Wire-guidance experiments followed

†This section is based on Reference [43].

a similar line to that in Britain and resulted in the Mk. 39 torpedo; this being a wire-guided version of the Mk. 27. This was eventually replaced by the 19 in. Mk. 37 which is the present standard submarine-launched weapon. The companion to the Mk. 39 is the Mk. 45, or *ASTOR*, which is capable of carrying a nuclear warhead.

Lightweight torpedoes appeared early in the U.S.A. with the Mk. 32 introduced in 1945 which weighed 1,200 lbs. The Mk. 43 introduced in the early 1950's was even smaller being 10 in. diameter and weighing less than 300 lbs. Its performance, especially its speed left much to be desired against the threat of the nuclear submarine and, although a higher speed modification was introduced the weapon was soon replaced by the Mk. 44.

Hydrogen peroxide was developed as a propulsion system and this eventually resulted in the Mk. 16 torpedo which was similar to the British *FANCY* weapon. The development of Mk. 16 was one of the most expensive torpedo projects yet evolved.

The present U.S. armoury of torpedoes includes:

(a) lightweight (560 lb.) Mk. 46/0 torpedo which can be delivered from a drone, Fig. 45, or *ASROC*, Fig. 46, the Orion P3 aircraft and from deck-mounted tubes, Fig. 47.

(b) The Mk. 44 lightweight torpedo. This is electrically propelled (in contrast to the Mk. 46/0 which is driven by hot gases generated by the burning of a solid charge).

TABLE 14. Summary of German non-electric torpedo developments

Type	*Propulsion*	*R*	*V*	*Remarks*
Klippfisch	Peroxide/piston engine	7,100	40	Used T1 engine. Tested 1942.
Mondfisch	Peroxide/jet	1,310	40	Coastal defence.
Steinfisch	Peroxide/turbine	7,650	45	Forerunner of Steinbutt.
Goldfisch	Peroxide/turbine	3,750	45	Small type for midget submarines.
Steinbutt	Peroxide/turbine	8,750	45	100 produced for service.
Goldbutt	Peroxide/turbine	3,390	50	Similar to Goldfisch.
Zaunbutt	Peroxide/turbine	?	?	Homing version. All plans lost in bombing.
Steinbarsch	Peroxide/turbine	7,100	50	100 produced for service.
K-butt	Peroxide/turbine	3,280	45	60 produced for midget submarines. Launched from external frame.
Steinwal	Peroxide/turbine	24,000	45	Nearly completed mid-1945.
Schildbutt	Peroxide/turbine	15,300	45	Sea water injection used.
LT 1500	Peroxide	2,200	40	Air-dropped, jet propelled.
LT 1000	Peroxide/turbine	5,500	50	Air-dropped.
M-5	Oxygen/piston	26,000	40	29 in. × 36 ft. Huge warhead.
G7a or T1	Air/radial	6,600	44	The standard war weapon.

(See table in previous article for further weapons)

(c) The Mk. 37 weapon, Fig. 48, which exists in ship launched and wire-guided, submarine-launched versions and which is a 19-in. diameter weapon.

(d) The Mk. 45, or *ASTOR*, torpedo which is a wire-guided, anti-submarine weapon capable of carrying a nuclear warhead.

Weapons under development include the Mk. 48 heavyweight, of which further details may be found in Reference[44].

Conclusion

History is usually interesting because of the insight it gives into the thoughts of previous generations. It can, and should be, valuable as a guide to future thinking. It is difficult to pick from the history of torpedo development definite lessons but perhaps the following are more obvious. Never underestimate a potential enemy's capabilities. Both the Germans and the British believed the last World War would be over too quickly to get new weapons into service and they started research on a large scale too late to play a significant part in the war. The Germans alone nearly salvaged their potential torpedo mastery with the Ingolin and homing weapons—more effort in 1940 and 1941 could have swung the course of the war far more in their favour but the anti-submarine aircraft patrol system perfected by Britain hit hard before our islands had been starved into submission.

As a second lesson it seems that interim weapons are poor value for money. It is better to wait an extra year or so for a good torpedo than push into service an indifferent one. The

TABLE 15. British projects, 1945 to 1970

Project	*Nature*	*Conclusion*
DEALER B	Air-dropped, anti-submarine	Mark 30, successful
Mk 30 mod 1	Improved Mk 30, £151,000 spent	Cancelled for U.S. Mk 43
ZOMBI	Submarine-launched, 30 in. dia.	Cancelled
ZETA	Air-dropped, anti-submarine	Cancelled
ZONAL	Flying anti-ship torpedo	Cancelled
ZOSTER	Anti-ship, air-dropped	Cancelled
DEWLAP	21 in. M.T.B. weapon	Cancelled
PENTANE	Air-dropped anti-submarine	Cancelled as Mark 21
BIDDER	Ship—or submarine—launched	Mark 20, successful
Mark 22	Cable set version of Mk 20	Cancelled for Mark 23
GROG/MACKLE	Wire-guided Mark 20	Mark 23, successful
NEGRESS	14 in. lightweight, air-dropped	Cancelled
FANCY	Peroxide Mk 8. Cost £899,000	Cancelled
BOOTLEG	Rocket propelled, anti-ship	Cancelled
HEYDAY	Rocket propelled	Cancelled
BARMAID	Ship-launched, anti-ship	Cancelled
ONGAR	Submarine-launched Mk 24	Under development
Mark 31	Air-dropped, to replace Mk 44	Cancelled
CAMROSE	Rocket propelled anti-torpedo weapon	Cancelled

FIG. 45. U.S. " DASH " system unmanned drone with Mk. 46 torpedo.

FIG. 46. "ASROC" booster carrying lightweight torpedo (Mk. 44 or Mk. 46).

FIG. 47. Modern triple tube launcher Mk. 32.

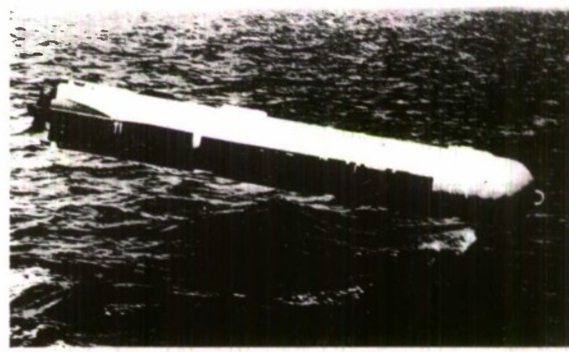

FIG. 48. U.S. Mark 37.

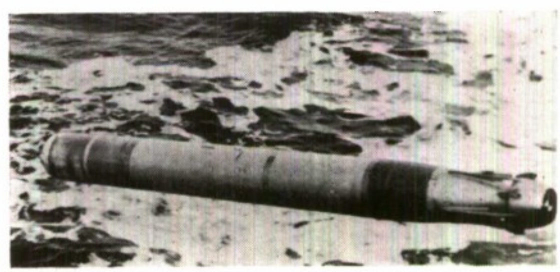

FIG. 49. U.S. Mk. 48, under development as replacement for Mk. 37.

interim weapon may take just as long to get into service anyway and its introduction will only further postpone, if not cancel altogether, the effective weapon on the drawing board.

New weapons must be based on well worked out requirements and operational policies.

Alas poor *PENTANE* . . . ! Fortunately these lessons seem now to be learnt but in case we should be tempted to err again the story of our past sins and their consequences are described above ! New weapons should also be part of an integrated weapon system—not just an appendage[45].

TABLE 16. Torpedoes on exhibition in Britain

Type	*Date (approx.)*	*Location*
Whitehead	1875	D.G.W., Bath
Whitehead	1875	Maritime Museum Greenwich
Whitehead (Experimental 12 in.)	1886	ditto
14 in. Fiume Mk IV	1884	R.N.A.D. Priddy's Hard
21 in. Mk 8	1940	ditto
21 in. Mk 9	1940	ditto
21 in. Mk 20	1958	ditto
PENTANE 21 in. Mk 21	1958	ditto
24½ in. Mk I	1927	ditto
18 in. Mk 30	1955	ditto
21 in. Mk 12		ditto
10 in. U.S. Mk 43	1963	ditto
Schwartzkopf	1885?	ditto
Marder	1944	ditto
Schwartzkopf	?	H.M.S. *President*
18 in. Mk 15	1942	R.N.A.S., Yeovilton
18 in. Mk 12	1940	R.A.F. Kenley
18 in. Mk 30	1955	ditto

'History is Bunk' seems to have been the motto in the torpedo world at least on the administrative side, during the 1950's for, of the superb collection of torpedoes from Britain, Germany (including *INGOLIN* and even a flapping wing torpedo), Japan, Italy, etc., on display at the T.E.E. Museum only one pre-1947 weapon survived to my knowledge. All the other old, and some very historic, torpedoes were scrapped on the order of 'Authority' despite the pleas of the engineers who had built up the collection. A similar fate overtook the collection at H.M.S. *Vernon*. An attempt is now being made to rebuild a torpedo collection at R.N.A.D. Priddy's Hard but, alas, the old R.G.F., Fiume and Whitehead masterpieces are now transformed, *via* the scrap merchants' yards into souvenir ashtrays from Margate and brass curtain rings. Thus is it demonstrated that even the deadly torpedo is overwhelmed by the power of the administrator's pen !

Table 16 sets out the known whereabouts of torpedoes ancient and not so ancient in Britain. Any information not included therein, or indeed, material additional to that published in all my articles will be gladly received. It is the author's intention to publish an expanded version of these articles in book form.

Acknowledgements

The idea and initial inspiration for these articles came from Mr. J. Lipscombe late of A.U.W.E., many photographs and literature were supplied by Messrs. W. Winsor, D. Miles and E. Manns of R.N.A.D., Priddy's Hard, Gosport and they are thanked in addition for their assistance when visiting the Armaments Museum. Lt. Commander Peter Gavin of H.M.S. *Vernon* has generously supplied information and photographs, of which Figs. 5 and 6 are examples; the library staff at A.U.W.E. are thanked for much assistance during my lunch-hour browsing through the stock of post-war reports; Mr. D. Harris is thanked for his assistance in copying old diagrams and photographs; and Mr. R. D. Wood of A.U.W.E. who very kindly read the manuscript and offered help with details of post-war work. All errors and omissions are mine however. My thanks also go to the Museum at R.N.A.S. Yeovilton, Mr. M. Willis of the Imperial War Museum and Mr. J. Lyons of the Maritime Museum, Greenwich as well as Mr. J. Wolstencroft of J & S Marine Ltd., for information on Whitehead's family. Above all these I must thank my wife Barbara for her patience during the 18 months taken to complete this project when many long evenings were spent by me at a noisy typewriter or buried under dusty reports!

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SURVIVAL FROM HYPOTHERMIA IN DIVERS

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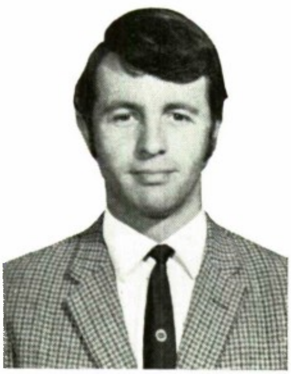

John Bevan (28) is a Scientific Officer and Head of the Environmental Factors Section at the Royal Naval Physiological Laboratory. Following his graduation with a B.Sc. Honours Degree of the University of London he has recently been awarded the M.Sc. Degree for his thesis on neurophysiological aspects of deep diving. Mr. Bevan who was a subject in the recent 1500 ft. world record simulated dive at RNPL is currently investigating thermo-physiological aspects of deep diving and is registered for the PhD Examination of the University of London. He is the Hon. Secretary of the Society for Underwater Technologys Southern Branch, and is a member of the Society's technological sub-committee. For his spare-time contributions to amateur sport-diving Mr. Bevan has been awarded the distinction of being the first " Diver of the Year " (1971) by the British Sub-Aqua Club.

Abstract

An account is given of measurements of the deep body temperature of divers before, during and following conventional air breathing dives to 3·1 metres (10 ft) and 30·5 metres (100 ft) using a temperature sensitive radio pill. A mild hypothermia was demonstrated (mean of 0·55 C below pre-dive level). Hypothermia is discussed as a major factor responsible for the deaths of individuals obliged to spend prolonged periods immersed in the sea. A graph indicating predicted maximum survival times that might be expected of " wet-suited " swimmers is given.

Introduction

Men immersed in the sea inevitably lose heat to the surrounding water. The rate at which this heat is lost depends mainly on first, the thermal insulation, both natural as in body fat and additional as in clothing (conductive heat loss) and second, the speed of water flowing past the body (convective heat loss).

An attempt to make good this heat loss is normally made by a variable heat generating system (metabolism) within the body. The metabolic output is, however, limited and under particularly adverse environmental conditions, such as the waters surrounding Britain, the heat loss can easily outstrip the heat production. The simple result is a lowering of body temperature.

This has two main effects, one good and one bad. First the temperature difference between the body and the environment is reduced, so tending to reduce slightly the rate of heat loss and second, the ability of the body to mobilise physiological counter-measures is impaired following a fall of only about 2°C. The body thus gradually, though involuntarily, relinquishes its sophisticated control of a worsening situation and submits itself to Newton's Law of Cooling.

An investigation was recently undertaken[1] to quantify the heat debt incurred by divers during conventional shallow water dives using compressed air breathing gas.

Materials and Methods

Subjects

Eleven male subjects participated in 21 experimental dives in the sea. Seven only of these subjects were able to complete dives to both 3·1 metres and 30·5 metres, due mainly to poor weather conditions. The subjects were under-graduates and post-graduates aged between 21 and 33 years.

Diving Equipment

Each subject wore a foamed neoprene wet-suit covered by an "Avon" single-piece, neck entry dry suit with suit inflation facility. Over this was worn a "Beaufort" carbon-dioxide inflation life-jacket and a knife was strapped to the lower leg. The subjects used a twin 40 cubic feet cylinder aqua-lung mounted on a back-pack harness and breathed the compressed air *via* an open-circuit, two stage, single hose, mouth-held demand valve.

Safety

All subjects were accompanied by a "buddy" diver and were supervised by an "attendant" on shore, who also maintained two-way voice communication with the "buddy" diver with a DUCS (diver underwater communication system, Royal Navy). Boat cover was maintained on all the 30·5 metre and most of the 3·1 metre immersions. Both the 3·1 metre and 30·5 metre sites were within 50 metres of the shore.

Temperature Measurement

The deep-body temperature of the subjects was monitored using a temperature sensitive "radio pill" (Model 7015, Rigel Research Limited, The Vineyard, Richmond, Surrey).

FIG. 1. Pre-dive radio pill monitoring.

The radio pill was cylindrical in shape, 26 mm in length and 8·8 mm in diameter. It was powered by a miniature battery (Mallory type RM 312 H) giving a pill life of 40 hours minimum. The pill was capable of operating over a frequency range of 320 to 420 kHz corresponding to a temperature range of 34 to 41°C with a sensitivity of 10 kHz per degree centigrade. The transmission of the pill was picked up by a ferrite rod aerial located on the seat on which the subject sat whilst underwater or was loosely attached to the subject's aqualung harness. A 100 metre length of co-axial cable carried the signal to the radio pill receiver/amplifier located on the shore. The attendant recorded the pill output frequency before, during and following each dive. Fig. 1 shows a subject kitted up in the dry suit and having his deep-body temperature measured.

Preparation of the Radio Pill

The pill was first calibrated in a series of thermostatically controlled water baths and a calibration curve or temperature plotted against output frequency produced. Following the calibration of a pill the battery was removed.

A pill was prepared for use by enclosing in a rubber finger stall and the end tightly tied off, ensuring that a minimum of air remained trapped within. The stall was reversed over the pill and a second tight knot placed over the end. The remaining portion of the stall was cut off and discarded. These steps are illustrated in Fig. 2.

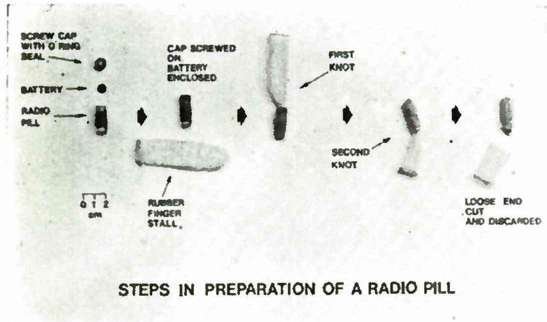

FIG. 2. Steps in preparation of a radio pill.

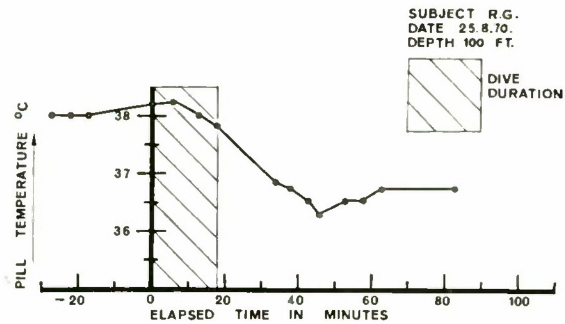

FIG. 3. Deep body temperatures of divers.

Diving Procedure

The subject swallowed the radio pill at least 30 minutes prior to diving in order to ensure that temperature equilibrium was reached with its environment before the immersion. The subject was assisted at all stages of his dressing in order to minimise his physical effort and consequent metabolic heat production prior to diving.

Once fully equipped the subject was transported to the diving site by boat. Both the subject and "buddy" divers left the surface together and on reaching the bottom the subject positioned himself on a chair previously moored to the bottom and maintained this position by placing a weighted belt across his lap. The seating arrangement for the subject was the same at both the 3·1 metre and 30·5 metre sites. Having completed various manual tasks requiring a minimum of physical effort the dive was terminated and both divers surfaced together. During this transitionary period, radio contact with the pill was lost until the subject arrived at the shore. Temperature monitoring was then resumed for a further period following the dive whilst the diver was undressed and allowed to change into dry clothing once more.

Results

Twenty-one individual dives, involving 11 divers, were monitored of which 13 were at 3·1 metres and eight were at 30·5 metres. The results of one such dive are illustrated graphically in Fig. 3. In the graph the dive duration is taken as the time elapsed between leaving the surface and arriving on the surface.

The mean ambient water temperatures which prevailed throughout the experiment were 12·5°C at 3·1 metres and 11·5°C at 30·5 metres. In spite of marked inter-individual variation observed in the degree of direct and indirect effects of cold exposure, a consistent thermal response pattern is apparent in most of the divers. This response consisted of a rise in core temperature occurring very soon after submersion followed by a steady fall. On completion of the dive the divers left the water and in spite of this action their core temperatures continued to fall for a period before returning to normal levels. This is more clearly seen in an averaged temperature profile of the 21 divers shown in Fig. 4.

This technique of monitoring the deep-body temperature was found to be easily accomplished. The sensitivity of the radio pill aerial and receiver was such that when an attendant was used who had been a subject on a previous day and who had not voided the pill, it was frequently possible to obtain satisfactory signals from both the subject and the attendant.

The maximum underwater range between subject and aerial over which a satisfactory signal could be obtained was found to be of the order of $1\frac{1}{2}$ metres.

Discussion

The thermal regularatory response observed in this experiment have been previously described by other workers. The observed initial elevation of deep-body temperature[2] is believed to be due to a shunting of blood away from the periphery into deeper tissues, thus effectively increasing the insulating value of the skin. Skreslet and Aarefjord[2] noted that there was no concomitant increase in metabolic rate that could account for this rise in temperature, thus supporting the hypothesis of increased insulation. Hardy and Soderstrom[3] however, maintained that the increased insulation did little to protect man

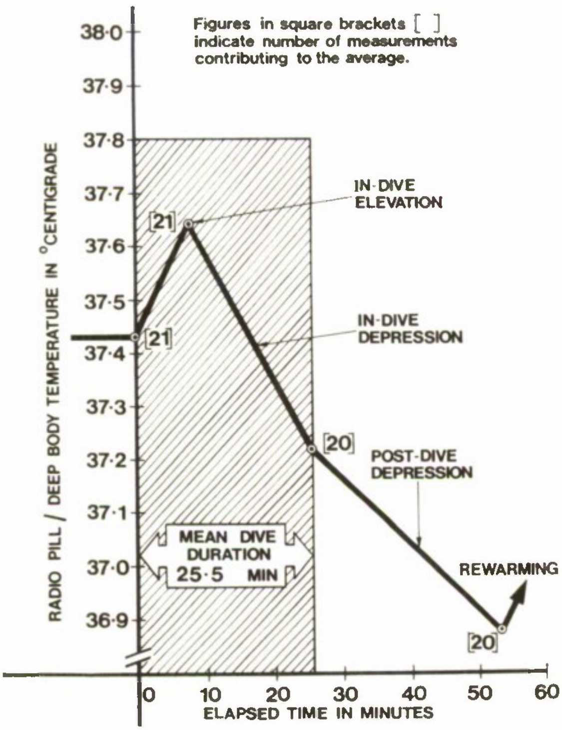

FIG. 4. Average response of deep body temperature.

against heat loss. In the light of more recent investigations the benefit of peripheral vasoconstriction can be seen to be largely dependent on the thickness of the subcutaneous fat.

Following the initial elevation, the deep-body temperature was observed in most cases to fall and on the completion of the dive continued to fall for a period afterwards to a mean of 0·55°C below pre-dive levels. This apparently paradoxical situation whereby the temperature continues to fall, even after removal from the cold water environment, is partly explained by Keatinge[4] who postulated that the skin temperature may remain low and thus maintain the thermal gradient responsible for the loss of deep-body heat. Furthermore, as the cold induced vaso-constriction of the skin subsided, the increase in the blood circulation would increase the conductivity of the superficial layers, thus briefly accentuating the fall in deep-body temperature. This after-drop in deep-body temperature was not of a very large magnitude in this experiment. However, it would be of great significance to persons suffering from acute hypothermia and could even be responsible for the death of the victims after rescue.[4]

Survival

The extremely, inhospitably cold environment that bathes the diver has mothered inventions of effective protection against its insidious dangers, among them the "wet-suit". Following the introduction of the wet-suit into world-wide use, this suit has now ramified from diving usage to many other water-borne activities, notably those of yacht crews and water skiers. Thus an increasing number of coastal accidents include survivors wearing effective thermal-insulating garments.

This is of enormous importance to Search and Rescue (SAR) organisations such as the Royal National Lifeboat Institution (RNLI). Whereas just a few years ago a lifeboat might confidently return to base after a period of searching knowing full-well that anyone remaining in the water after a particular period would most certainly be dead from hypothermia, today those survivors might be wearing wet-suits.

The question therefore arises, how long should a search for such individuals be maintained? The answer is particularly elusive, mainly due to an almost complete lack of information in this new field. To quote one of the few data available (reported by the *Daily Telegraph*, 20.11.1967) " The skin-diver Mr. ...., 29, of Penzance who disappeared at noon on Saturday .... scrambled ashore at 4.30 a.m. (Sunday) .... after 16½ hours in the water ". This man was in relatively good condition when he came ashore having been exposed to cold water for a period more than four times longer than he could have hoped to have survived had he not been wearing a wet-suit.

In the absence, therefore, of sufficient background information, one can only calculate and extrapolate from existing knowledge as to what might be the maximum survival times that a wet-suited man can expect. The closest relevant information comes from G. W. Molnar[5] from a survey of several hundred reports of survival in sea-water of different temperatures between 1942 and 1945, Molnar was able to construct a graph showing the maximum survival time that might be expected of ship wreck survivors. This graph is reproduced in Fig. 5. It can be assumed that the longest lasting survivors are those with the

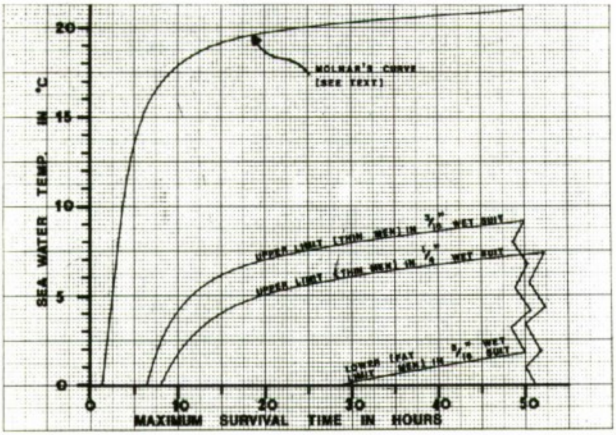

FIG. 5. Estimated Maximum Survival Times of Wet-Suited Men immersed in Sea-Water at Various Temperatures.

most insulation. Thus an obese survivor has the best chance of survival. If it is now assumed that the maximum total insulation that one can have in water without wearing special clothing is of the order of 0·5 Clo then the estimated maximum survival time of wet-suited swimmers may be calculated and this I have done in Fig. 5.

It can be seen from this illustration, that the survival times of wet-suited survivors are enormously longer than those of their relatively unprotected counterparts.

In conclusion, as a useful but regrettably, purely academic exercise, reference may be made to the catastrophic sinking of the *Titanic,* April 1912. Keatinge[4] noted: only 712 of the 2201 people on board were able to leave the ship in lifeboats or to swim to a lifeboat. Within an hour and 50 minutes of the sinking the *Carpathia* reached the scene .... She was able to rescue almost all the people in the boats, but everyone of the 1489 people who were still in the water was dead.

Assuming the sea water temperature was of the order of 0°C, and just supposing that all those who leapt in the sea that night had put on a wet-suit then by referring to Fig. 5 it can be inferred that the search for survivors might have been a little more fruitful.

Acknowledgement

I am indebted to the United London Hospitals Diving Group for the opportunity of including the temperature sensitive radio pill work in their experiments.

Grateful acknowledgement is extended to the Medical Research Council and the Royal Naval Air Medical School for the provision of the radio pill equipment.

The enthusiastic co-operation of the diving subjects is also very much appreciated.

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MATERIALS FOR EXTREME ENVIRONMENTS

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Introduction

The development of modern technology in the past 30 years has placed increasing demands upon the technologist and materials scientist for materials which can withstand the extreme environmental conditions in which they will operate. Economic factors have placed additional demands on the ingenuity of both the materials technologist and the designer and fabricator.

The major areas where materials evolution has been most dramatic are resistance to corrosion and to high and cryogenic temperatures and in nuclear reactor materials. The economic implications of corrosion have been highlighted by a recent Government sponsored survey which has put the cost of corrosion in the U.K. at greater than £1600 million per annum. In this connection it should be noted that the natural environment is one of the most severe in relation to corrosion. The technology of high and low temperatures and nuclear reactors has developed mainly within the past 30 years and it seems likely that in the next 30 years this trend will continue with perhaps growing emphasis on cryogenics.

Corrosion in Saline Environments

There are very few engineering metals which are immune to corrosion in sea water. Steel has a corrosion rate of 150μm/yr, and copper 50μm/yr, the latter being acceptable for many applications. Zinc coating of steel is an effective means of protection, since the corrosion of zinc is about 30μm/yr in sea water, and also allows steel to be used with aluminium without causing serious galvanic corrosion. More corrosion-resistant copper alloys such as Cu, 10 Ni, 1 Fe and Cu, 30 Ni, are used where water velocities are sufficient to cause impingement attack, and aluminium brass where good heat transfer is required. These materials are widely used in heat exchangers, although very occasionally trouble is encountered in polluted or anaerobic H_2S. bearing waters. Aluminium bronzes formulated to resist de-aluminification selective attack with nickel or silicon additions are used when high strengths are required. Gun-metals, Cu/Sn alloys with zinc and sometimes lead additions are used where good castability and corrosion-resistance are both necessary. It might be thought that stainless steels would be the answer to corrosion problems in sea water, in view of their excellent behaviour in many other environments, but differential aeration local attack or " crevice corrosion " can be a very serious problem. Although worst with martensitic/ferritic 13% Cr steels, none of the austenitic materials, 18 Cr, 8 Ni, etc is immune to crevice corrosion, and these materials are not suited for general service immersed in sea water, although there are a few well-established uses where crevice corrosion has not proved to be a difficult problem. A few highly alloyed and rather expensive materials, such as Inco 625 (60 Ni, 21 Cr, 9 Mo, 5 Fe, Nb + Ta 3·5) combine high strengths and immunity to corrosion, including crevice corrosion, and are used when any corrosion is unacceptable. Titanium and its alloys are practically immune to attack in sea water, but their relatively high cost has limited their use.

Aluminium and some Al/Mg alloys (up to 5% Mg) are quite resistant to sea water. Stronger alloys (Al/Si/Mg) have slightly greater corrosion rates in saline environments and are significantly stronger. In general, very high strength Al alloys have unacceptable corrosion behaviour, and sometimes suffer from stress corrosion. Used in combination with other metals, serious galvanic corrosion of aluminium can occur, and even deposition of dissolved copper from solution can cause this.

Another environment resembling sea water and the severity of its corrosion problems is the tissue fluid of animals. The use of certain stainless steels here is accepted practice, although crevice corrosion and galvanic interaction between different steels have occasionally been encountered. Vitallium, a Co/Cr alloy, has been used successfully for many years and titanium has shown promise. One problem is that polymeric materials, which in many cases are satisfactory in saline environments, tend to undergo enzymatic degradation, and it has been claimed that there is some effect on every material and that such attack, *e.g.* on certain polyurethanes, can be severe.

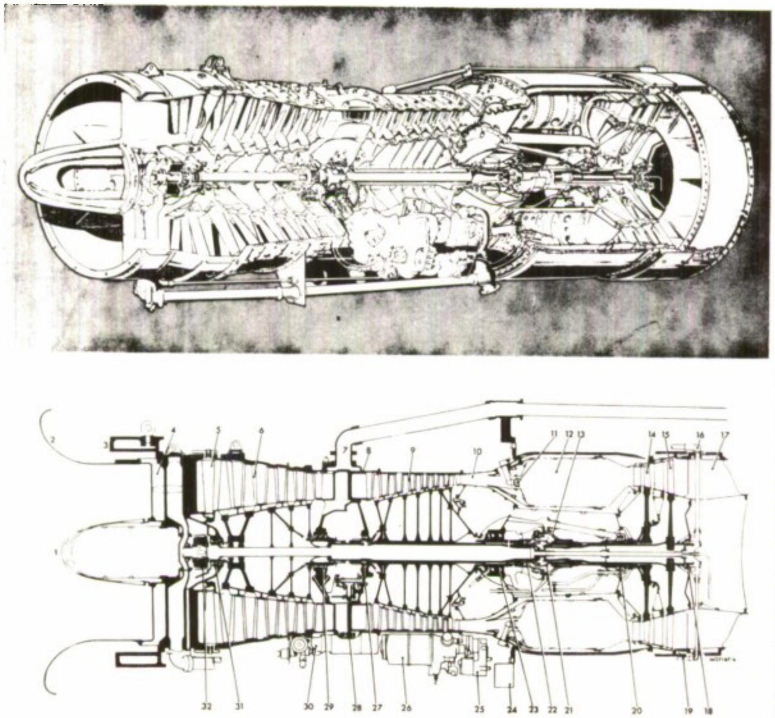
Corrosion in Atmospheric and Fresh Water Environments

Corrosion of materials in inland atmospheric exposure and fresh water is less severe than in marine conditions. The action of SO_2 and acidic dust particles has been shown to be responsible for the corrosivity of industrial atmospheres for ferrous materials, but corrosion can be controlled successfully with effective paint or polymer coatings or sacrificial metal coatings, such as zinc, aluminium and cadmium. The use of stainless steel and aluminium is well-established. The choice of materials with fresh water depends upon the corrosivity of the water, which is controlled in a complex manner by the total dissolved salts, its magnesium and calcium content and CO_2 and organic material content. Cast iron, copper and galvanised coatings may be attacked in various local waters and dezincification of brasses, a severe problem in sea water, can be encountered in certain fresh waters. Although complex, these problems are now well understood, but informed advice is necessary when materials are selected.

Materials for High Temperature Environments

Owing to oxidation, creep and loss of strength, the use of steel becomes difficult at high temperatures. Special alloys and coatings. *e.g.* sprayed Al, diffused Cr, allow use to higher temperatures but ultimately alloys of high non-ferrous content have to be used. Chromium additions confer the best oxidation resistance, but nickel lowers the thermal expansion coefficient of the alloy, thus improving the behaviour in thermal cycling.

The best oxidation resistance at temperatures above 5-600° is given by materials with higher alloy contents than the 18 Cr, 8 Ni, steels, *e.g.* 310 (25 Cr, 20 Ni) or 330 (15 Cr, 35 Ni, 1 Si) types. Optimum performance at the highest temperature at which use of metals is practicable (900 - 1,150°C) is given by nickel chromium alloys (80 Ni, 20 Cr - the original " Nimonic ") or iron containing alloys such as Incoloy 800 (32 Ni, 21 Cr) and Hastelloy X (50 Ni, 21 Cr, 18 Fe, 9 Mo, 1 Co). Other nickel and cobalt alloys, developed to yield optimum mechanical and creep resistance properties at temperatures up to 900°C, also have good oxidation resistance. The presence of SO_2, CO_2, H_2O and chloride in general tend to increase attack, sometimes up to ten times. Sulphur can cause serious penetration of the metal beneath the oxide scale, especially if chloride is present, and increasing Cr content is a promising remedial measure. At temperatures above 1,000°C the use of ceramics may be considered. Alumina is useable, depending on purity, up to 1,800°C, although care has to be taken to avoid thermal stress failure and



1. Nose fairing
2. Air intake flare
3. Front mounting ring
4. Air intake
5. Compressor entry guide blade
6. L.P. compressor (five stage)
7. Cooling air bleed to power turbine
8. Intermediate casing
9. H.P. compressor (seven-stage)
10. Delivery casing
11. Burner
12. Combustion chamber
13. H.P. compressor coupling
14. 1st stage turbine
15. 2nd stage turbine
16. Cooling and pressurizing air bleed from H.P. compressor
17. Exhaust annulus
18. 2nd stage turbine rear bearing
19. Oil drain
20. 1st stage turbine bearing
21. L.P. compressor coupling
22. 2nd stage turbine front bearing
23. H.P. compressor rear bearing
24. Mid-engine support ring
25. Fuel flow distributor
26. Fuel filter
27. H.P. compressor rear bearing
28. Auxiliaries drive shaft
29. L.P. compressor rear bearing
30. Oil pump assembly
31. L.P. compressor front bearing
32. Oil separator

FIG. 1. Typical high performance gas turbine engine.

creep and sintering deformation. For thermal shock environments the use of silicon nitride is preferred because of its low thermal expansion up to temperatures of 1,500°C, oxidation of Si_3N_4 being only slow up to this temperature. Materials with expansion behaviour intermediate between these two materials are mullite, zircon and silicon carbide, the latter having very advantageous thermal conductivity. Above about 800°C, only the use of zirconia or yttria is practicable in oxidising environments, although in non oxidising conditions or short exposures carbon and the refractory carbides and borides of zirconium, titanium, tantalum and niobium have been used satisfactorily.

Corrosion in Chemical Plant

The behaviour of materials in chemical plant cannot be predicted from theory since factors such as concentration, temperature, pressure, the presence of trace elements, etc., have a significant effect on behaviour. Thus materials have to be selected on the basis of implant corrosion trials in actual plant or of laboratory tests in a simulated environment. Close attention to detail in such evaluation procedures is important, since, for example, the presence or absence of moisture and effects such as heat transfer rate in process vessels can have marked effects. Many excellent compilations of data exist and guidance on materials selection can be obtained from literature sources. A very wide range of materials exist for specific applications in corrosive chemical environments. Such materials range from mild and low and high alloy steels to nickel base alloys, high molybdenum alloys, tantalum, tungsten and the precious metals. In selecting materials, due regard must be paid to fabricability since some materials, such as unstabilised austenitic stainless steels, may suffer "weld-decay" or similar effects in specific environments. When employing materials in combination, electrochemical corrosion may lead to accelerated corrosion of one of the materials and hence care should be taken to employ only compatible combinations of materials.

Economic Use of Corrosion Resistant Materials

The high cost of special materials has focused attention on the use of clad steels in corrosive environments. Techniques such as roll-bond cladding, weld-cladding and the use of strip linings plug welded or argon spot welded to the low cast supporting material are now commonplace. Such techniques permit the corrosion resistant material to be only sufficiently thick to resist the action of the aggressive environment, strength being provided by the steel backing. Care has to be exercised in weld fabrication of clad steel since dilution of the weld metal on the corrosion resistant side by alloying with the steel backing may lead to reduced corrosion resistance of weld metal. Explosive cladding using explosives costing £0·1 to £0·15 per pound appears an attractive method for low cost cladding but the process requires further development to produce efficient bonding on surfaces having double curvature. Explosive welding also offers advantages in eliminating problems of weld metal dilution and selection of weld filler metals.

The use of plasma or flame sprayed metallic coatings is also effective in many circumstances. Ceramic and polymer coatings may also be applied using spraying or alternative techniques.

The use of impressed current cathodic protection or sacrificial anodes provides a further technique for reducing the effects of corrosion.

High Temperature Materials

Absolute zero is the limit of cryogenic temperature but no apparent limit is in sight for high temperatures. Atomic explosions generate temperatures of the order of 60×10^6 °C and plasma torch devices can achieve in excess of 10×10^3 °C. The technology of high temperature materials has made rapid strides in the past 30 years with the advent of the gas turbine (Fig. 1) and other aerospace developments and the desire to utilise high temperatures in nuclear reactor systems.

Metals and ceramics have finite temperature limits, tungsten (m.p. 3400°C) and rhenium (m.p. 3170°C) being the highest melting point metals and graphite (sublimation temperature 3650°C), hafnium carbide (m.p. 3890°C) and zirconium monocarbide (m.p. 3540°C) representing the upper limits of the refractory ceramic materials. The behaviour of materials at high temperatures is stress, time and temperature dependant and because of these synergistic effects materials must be limited to temperatures not greater than 0·5 to 0·75 of their melting temperatures if useful design stress levels and economically viable service lives are to be obtained. Where stresses are low or short lives are adequate then somewhat higher temperatures may be permissible.

In considering extreme high temperature conditions stress/time/temperature criteria must be related to compatibility with the environment since oxidation or related effects may limit the use of materials having attractive high temperature mechanical properties. Consideration must also be given to mechanical fatigue properties, thermal shock or fatigue resistance, structural stability and freedom from embrittling effects after long term exposure to high temperatures. Fabricability in the required form is also an important economic and practical consideration.

Advanced aircraft gas turbine engines[1] operate at turbine entry temperatures of up to 1650°K and by the mid '70s may reach 1750°K. The turbine blades may be expected to sustain a stress of 45 to 65 MN/m^2 (15·7 to 22·4 ksi) for several thousands of hours in a highly oxidising environment.

Nickel base alloys in both wrought and cast forms continue to be the most widely applied turbine blading materials. This pre-eminence of nickel alloys is essentially due to the strengthening mechanism first developed in the U.K. in the early Nimonic type alloys, *i.e.* precipitation of the γ' phase ($Ni_3(Al, Ti)$), which provides resistance to loss in strength due to overtemperature excursions. This mechanism of strengthening is used in conjunction with solid solution hardening. The weaker cobalt base alloys have found application in more lowly stressed areas such as nozzle vanes. Some typical nickel and cobalt base alloys together with their comparative stress-rupture properties are given in Table I[2, 3, 4, 5]. In general turbine blade alloys have improved at the rate of about 10°C per annum but turbine entry temperatures are now above the melting points of the available materials and air cooling of the blades is necessary and permits gas temperatures about 300°C hotter than would be permissible without cooling. Improvement in cooling techniques permits gas temperature to increase at the rate of 30 to 40°C per annum. The use of porous surfaces and transpiration cooling may permit further significant improvement in the future.

TABLE 1. Nickel and Cobalt Base Super Alloys—Rupture Strengths.

NOMINAL CHEMICAL COMPOSITION %

MATERIAL (c) = cast	C	Cr	Ni	Mo	W	Nb	Ta	Al	Ti	B	Zr	Fe	Co	Other
NICKEL BASE														
Nimonic 90	0.1	20	Bal	-	-	-	-	1.2	2.4	-	-	-	16	-
Nimonic 105	0.2	13.5/16	"	4.5/5.5	-	-	-	4.2/4.8	0.9/1.5	-	-	1	18/22	-
Nimonic 115	0.15	15	"	3.5	-	-	-	5	4	-	-	-	15	-
Udimet 700	0.07	15	"	5.3	-	-	-	4.3	3.2	0.02	0.04	-	17	-
B1900 (c)	0.10	8	"	6	-	-	4	6	1	0.015	0.10	-	10	-
MAR-M-200(c)	0.08	9	"	-	12.5	1	-	5.5	2	0.025	0.05	-	10	-
IN100 (c)	0.18	10	"	-	3	-	-	5.6	5.2	0.015	0.09	-	15	0.65V
M22 (c)	0.13	5.7	"	2	11	-	3	6.3	-	-	0.6	1max	-	-
IN597	0.05	25	-	2	-	1.0	-	1.5	3.2	Present	Present	-	20	-
COBALT BASE														
X40 (HS31)	0.5	25.5	10.5	-	7.5	-	-	-	-	0.01	-	2	Bal	-
X45	0.25	25.5	10.5	-	7.5	-	-	-	-	0.01	-	2	"	-
FSX414	0.35	29.5	10.5	-	7	-	-	-	-	0.01	-	2	"	-
WI52	0.45	21	1.0max	-	11	2	-	-	-	-	-	2	"	-
MAR-M-302(c)	0.85	21.5	-.	-	10	-	9	-	-	0.005	0.2	-	"	-
MAR-M-509(c)	0.6	24	10	-	7	-	3.5	-	0.2	-	0.5	-	"	-

RUPTURE STRENGTH

MATERIAL (c) = cast	815°C				870°C				980°C				1095°C			
	100 h		1000 h		100 h		1000 h		100 h		1000 h		100 h		1000 h	
	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi
NICKEL BASE																
Nimonic 90	239	34.7	154	22.4	139	20.2	77	11.2	-	-	-	-	-	-	-	-
Nimonic 105	324	47	224	32.5	139	20.2	134	19.5	68	9.9	32	4.7	-	-	-	-
Nimonic 115	402	58.3	309	44.8	301	43.7	201	29.1	121	17.5	70	10.1	-	-	-	-
Udimet 700	400	58	296	43	290	42	200	29	110	16	52	7.5	-	-	-	-
B1900 (c)	503	73	379	55	386	56	255	37	179	26	106	15.4	-	-	-	-
MAR-M-200(c)	524	76	413	60	400	58	290	42	186	27	131	19	76	11	45	6.5
IN100 (c)	503	73	379	55	379	55	255	37	172	25	103	15	44.8	9	-	-
M22 (c)	510	74	388	57	390	57.6	281	41.7	-	-	-	-	77.3	11.5	31	4.5
IN597	324	47														
COBALT BASE																
X40 (HS31)	179	26	138	20	134	19.5	103	15	76	11	55	8	-	-	-	-
X45	131	19	103	15	96	14	69	10	48	7	31	4.5	-	-	-	-
FSX414	152	22	117	17	110	16	83	12	55	8	34	5	21	3.1	-	-
WI52	-	-	-	-	172	25	152	22	96	14	76	11	35	5	-	-
MAR-M-302(c)	276	40	207	30	207	30	158	23	110	16	76	11	41	6	28	4
MAR-M-509(c)	269	39	228	33	200	29	138	20	117	17	90	13	55	8	38	5.5

In general as alloys have become more creep resistant, oxidation and sulphidation resistance has degraded and aluminised coatings of nickel-aluminide or aluminium-chromium alloy have been employed for protection at high temperatures. Higher chromium alloys such as IN597, which in cast form is equivalent in creep properties to Nimonic 115, and the cobalt alloy FSX414 have been developed to provide enhanced corrosion resistance in industrial and marine engines. In modifying compositions to secure greater corrosion resistance care is necessary to avoid alloys which embrittle on exposure at temperature. It is largely because of poor oxidation resistance that materials with thoria dispersion strengthening such as TD nickel and TD nickel chromium, which have attractively flat stress-rupture temperature relationships, have not been used.

Nozzle vanes and turbine blades require to be resistant to thermal shock and hollow nozzles are often employed to avoid problems of thermal stress.

Refractory metals such as niobium, molybdenum, tantalum and tungsten and their alloys have attractive high temperature properties for application in turbines but all are prone to rapid oxidation and no satisfactory long life coatings have yet been found. Chromium and its alloys have high oxidation resistance, low density, high melting point and attractive strength properties but are brittle at room temperature and rapidly embrittle by nitrogen absorption at high temperatures and hence are at present unsuitable for turbine applications.

Improvement in blade materials in the next decade is likely to come from application of techniques such as directional solidification of existing alloys or of eutectics or intermetallic compounds, dispersion strengthening with thoria or yttria and by wire, fibre or filament reinforcement. Carbon fibres are unlikely to have sufficient oxidation resistance but silicon carbide filaments may prove useful. The improvement in properties due to directional solidification[6] can be seen from Table 2.

TABLE 2.

Creep and Stress-Rupture Properties of Directionally Solidified and Single Crystal Mar-M-200

Structure	*Stress 207 Mn/m² (30 ksi at 982°C*		
	Life h	*Elong %*	*Min Creep Rate in/in/h*
Equi-axed	35·6	2·6	$23{\cdot}8\times10^{-5}$
Directional	67	23·6	$25{\cdot}6\times10^{-5}$
Single Crystal	107	23·6	$16{\cdot}1\times10^{-5}$

The recent discovery of the powder metallurgy technique of mechanical alloying creates new possibilities of producing improved alloys of greater strength than can be achieved by conventional means[7].

Ceramic materials have an attractive combination of properties including low density, high melting point, high oxidation resistance and retention or enhancement of strength at high temperatures, but unfortunately have no ductility and hence are fragile. Silicon nitride (Si_3N_4) is probably the most attractive ceramic, having excellent thermal shock resistance (due to low thermal expansion coefficient) good retention of strength and oxidation resistance up to at least 1500°C and a versatile fahrication technology. The availability of forms ranging from fully dense to low density foamed structures provides the possibility of application as a high temperature structural material or as insulation in gas turbines or rocket engines. The development of a " plastic " form of mouldable silicon powder compact has enabled thin continuous sheet or tape to be produced. This can be formed into a multilayer extended surface matrix material, for applications such as rotary regenerative heat-exchangers, prior to reaction to the silicon nitride ceramic. The high hot hardness of silicon nitride also offers the possibility of high temperature bearings and it has been found to have a low coefficient of friction when the surfaces are suitably lapped. A recent development is reinforcement of silicon nitride with high modulus refractory silicon carbide filaments to provide enhanced toughness and offers promise of alleviating one of the major disadvantages of ceramics. *i.e.*, fragility.

The various forms of carbon and graphites are attractive materials for extreme temperature conditions [8, 9]. Low density, high strength which increases with temperature, high sublimation temperature and excellent thermal shock resistance have made these materials attractive for uncooled rocket nozzles and re-entry heat shields for space vehicles. Pyrolytic carbon is particularly attractive due to its anistropy of thermal and other properties. Parallel to the deposition plane conductivity is substantially metallic but is two orders of magnitude lower in the thickness direction. This property permits flexibility of design in relation to thermal resistance.

One of the most extreme high temperature conditions occurs in the heat-shield of space vehicles during re-entry of the earth's atmosphere when velocities may be 39,600 Km/h (24,600 m.p.h.). This condition leads to equilibrium temperatures above the destruction temperature[8] of most materials. The equilibrium temperature with pyrolytic carbon is below its sublimation temperature but other materials can be effective because they " ablate " *i.e.* they char, melt, vaporise and peel off. This process removes heat and protects the underlying structure. Ablative materials are generally composites of silica, alumina, glass fibres, asbestos or other refractory fibres bonded with polymer resin.

The need for nuclear reactor fuels of high dimensional stability and fission product gas retention has led to the developement of oxide and carbide ceramic fuels which owing to their relatively low thermal conductivity may operate at centre temperatures as high as 1800°C even in water cooled or steam generating reactors where the coolant temperature may be only about 320°C. The pursuit of reactor types of improved thermal efficiency and lower capital cost has resulted in the use of self bonded and pyrolytic silicon carbide and pyrolytic carbon as the fuel cladding materials for temperatures up to 1500°C in high temperature helium cooled systems. Pyrolytic coatings on spherical fuel particles of 500 to 1000 micro-metres diameter may be of the order of 100 to 125 micro-metres total thickness (the thickness of newspaper) but have excellent mechanical stability and fission product retention.

Cryogenic Materials

The foundations of low temperature technology or cryogenic engineering were laid in 1884 when oxygen and nitrogen were first produced by fractional distillation of liquid air. In 1898 Dewar liquified hydrogen and in 1908 H. K. Onnes liquified helium at a temperature of 4°K. Absolute zero is -273.16°C (O°K) and it is only in comparatively recent years that temperatures close to this lower limit have been achieved. Some sub-zero temperatures of current technological significance are listed in Table 3. The advantage of handling gases in liquid form is clear from the gas/liquid volume ratios.

Materials increase in strength and elastic modulus as temperatures fall below ambient but not all remain ductile. In general materials having a body centred cubic crystal structure (*e.g.* iron, molybdenum, tungsten) or a close

TABLE 3.
Some Sub Zero Temperatures of Technological Importance.

Chemical Substance or Process	*Liquifying Temp. Boiling Point or Operating Temp. °C*	*Gas/Liquid Volume Ratio*
Ammonia	—33·4	—
Propane	—42·3	316
Propylene	—47·7	—
Carbonyl Sulphide	—50·2	—
Chlorine	—55	—
SO_2 dewaxing in refining	—60	—
Hydrogen sulphide	—59·7	—
Carbon dioxide	—78·5	—
Acetylene	—84	—
Ethane	—88·7	—
Purification of nitrous oxide	—90	—
Butyl rubber production	—100	—
Ethylene	—104	485
Krypton	—153·2	—
Methane	—162	—
Natural Gas	—162	600
Oxygen	—183	843
Argon	—186	—
Fluorine	—188	—
Nitrogen	—196	683
Neon	—246	—
Dueterium	—249·6	—
Hydrogen	—253	850
Helium	—269	753

packed hexagonal structure (*e.g.* magnesium, zinc) become brittle at low temperatures and face centred cubic metals (*e.g.* aluminium, copper, nickel) remain ductile. There are exceptions however and to demonstrate the suitability of a material for low temperature service the properties must be evaluated. The growth of cryogenic engineering in the past thirty years has led to extensive literature on properties. Important properties at low temperatures include conventional mechanical strength, elastic modules and ductility, fatigue strength, impact behaviour, notch ductility and resistance to crack propagation, thermal conductivity and expansion. In addition fabricability by brazing or welding and the properties of the resulting joints are important as well as any adverse effects which may arise from structural changes in heat-affected zones of the parent material. The effect of long term exposures at low temperatures is also significant as well as that of thermal cycling from ambient to sub-zero levels since some materials, such as certain types of stainless steel, may be unstable and embrittle due to transformation effects. Economic factors are important in commercial applications such as liquid gas storage or transport but in specialised aerospace applications specific strength (strength/density ratio) may be of greater significance. Corrosion rates reduce with reduction in temperature and corrosion is not normally a serious factor but in certain instances may have to be taken into account since the corrosion rate in the cryogenic substance may be small but significant or corrosion may occur from the environment in contact with the outside of the cryogenic containment.

The mechanical properties at low temperatures of a selection of metals and alloys are given in Table 4, and the chemical analyses of these materials are presented in Table 5. In general fatigue properties improve with decreasing temperature in parallel with the increase in tensile and yield properties. Conventional mechanical properties may indicate useful ductility at low temperatures but other data are required to assess behaviour under shock loads or triaxial stresses. Charpy Vee notch impact data together with notched tensile strength (see Table 4) provide some indications of performance. The cast nickel-aluminium-bronze in Table 4 shows evidence of serious degradation of impact value at low temperatures and hence must be considered suspect for cryogenic applications. To examine the notch ductility behaviour and resistance to crack propagation under severe service conditions of low temperature and complex stresses more sophisticated tests such as the Tipper notched tensile test and the U.S. Navy tear test have been evolved. In such tests a

TABLE 4. Mechanical Properties of Some Typical Materials at Low Temperatures.

Material	Form and Condition	Test Temperature	0.2% Proof Stress or Yield Stress		Tensile Strength		Elongation	Reduction of Area	Young's Modulus		Shear Modulus		Notched Tensile Strength		Charpy Vee Impact		Ref.
		°C	MN/m²	ksi	MN/m²	ksi	%	%	GN/m²	10⁶ psi	GN/m²	10⁶ psi	MN/m²	ksi	J	ft.lb	
Aluminium BS 1470 SIC	Sheet-annealed	20	20	2.9	65	9.4	41										10
		-78	22.5	3.3	70	10.2	42										
		-196	25	3.6	155	22.5	48										10
BS 1470 N3	Sheet-annealed	20	35	5.1	100	14.5											
		-78	40	5.8	110	15.9											
		-196	50	7.3	200	29.1											
BS 1477 NP5/6	Plate 6.35 mm	20	204	29.6	345	50.2	16.5	17									11
		-78	259	37.6	352	51.2	20.5	33.5									
		-196	287	41.7	468	68.0	3.5	32									
5083	Plate-annealed	20	210	30.5	305	44.3	7										10
		-78	220	32.0	315	45.8	13										
		-196	260	37.8	420	61.1	14										
BS 1470-H30	Sheet - WP	20	305	44.3	400	58.1	17										10
		-78	350	50.9	430	62.5	12.5										
		-196	420	60.1	505	73.4	17										
7039	Sheet - WP	20	410	59.6	460	66.9	13.5										10
		-78	450	65.4	500	72.7	12										
		-196	500	72.7	595	86.5	10										
Copper OHFC	Bar 19.05 mm dia. Annealed	20	75.0	10.9	221.5	32.2	53.8	86.2									12
		-78	80.0	11.6	268.9	39.1	53.2	84.5									
		-196	88.0	12.8	359.1	52.2	60.1	84.1									
		-253	90.1	13.1	417.5	60.7	68.9	83.0									
Admiralty Brass	Bar 19.05 mm dia. Annealed	20	72.9	10.6	308.2	44.8	86	81	100.7	14.6	41.0	5.94	370.1	53.8	151.9	112	12
		-78	86.7	12.6	341.2	49.6	91	79	102.7	14.9	42.4	6.15	404.5	58.8	153.2	113	
		-196	128.6	18.7	444.4	64.6	96	73	106.9	15.5	44.7	6.48	517.3	75.2	154.6	114	
		-253	143.1	20.8	528.3	76.8	99	68	110.3	16.0	45.2	6.55	614.9	89.4	154.6	114	
		-269	145.1	21.1	540.7	78.6	92	72	111.7	16.2	-	-	592.9	86.2			
Naval Brass	"	20	213.2	31.0	435.4	63.3	37	52	96.5	14	39.7	5.76	515.0	74.7	51.5	38	12
		-78	232.5	33.8	463.6	67.4	37	54	100.0	14.5	40.9	5.94	584.6	84.8	57.0	42	
		-196	261.4	38.0	553.0	80.4	44	48	102.0	14.8	42.5	6.16	694.3	100.7	51.5	38	
		-253	327.4	47.6	723.6	105.2	41	42	103.4	15	43.2	6.26	785.3	113.9	47.5	35	
		-269	300.6	43.7	685.1	99.6	40	46	104.1	15.1	-	-	795.6	115.4			
90/10 Cupro Nickel	"	20	147.2	21.4	341.2	49.6	37	79	122.0	17.7	-	-	448.1	65	154.6	114	12
		-78	169.9	24.7	367.3	54.7	42	77	-	-	-	-	504.0	73.1	153.2	113	
		-196	170.6	24.8	495.3	72.0	50	77	134.4	19.5	-	-	601.2	87.2	155.9	115	
		-253	207.7	30.2	567.5	82.5	50	73	-	-	-	-	667.4	96.8	157.3	116	
		-269	171.3	24.9	554.4	80.6	5[illegible]	73	141.3	20.5	-	-	689.5	100			
70/30 Cupro Nickel	"	20	128.6	18.7	397.6	57.8	47	66	151.7	22	-	-	547.4	79.4	155.9	115	12
		-78	152.7	22.2	467.7	68.0	48	70	-	-	-	-	624.0	90.5	154.6	114	
		-196	217.4	31.6	617.7	89.8	52	70	158.6	23	-	-	778.4	112.9	154.6	114	
		-253	262.1	38.1	709.2	103.1	51	66	-	-	-	-	879.8	127.6	154.6	114	
		-269	275.8	40.1	719.5	104.6	48	65	160.0	23.2	-	-		130.5			

range of stress concentration factors (typically Kt=4 to Kt=14) can be employed by control of the sharpness of the notch(s). The appearance of the fracture (whether ductile or brittle, etc.) provides important information in addition to the measured values of such parameters as stress, energy and ductility. Typical Tipper and tear test data are given in Tables 6 and 7. Essentially such tests indicate whether ductility is sufficient to allow local yielding to relieve stress-concentrations, which if unrelieved, might lead to catastrophic failure.

Cryogenic materials may be classified into structural materials which retain useful mechanical properties at low temperatures and special materials which only develop their important characteristics at close to liquid helium temperature *e.g.*, superconductors and cryo-conductors.

At low temperatures conventional mild and low alloy steels undergo a transition from ductile to brittle behaviour as typified by many recorded instances of brittle failure. Metallurgical structure is important and the transition temperatures of tempered martensitics are lower than those of normalised or annealed structures. In addition steel melting and rolling practice, fine grain size and certain alloying elements have an important and beneficial influence. Nickel is the most important element for lowering transition temperatures but low carbon content is also beneficial. Typical levels of nickel employed in structural steels for low temperatures together with limiting temperatures are as follows:—

Nickel %	Test and Minimum Use Temperature °C
2·25	−73
3·5	−101
9·0	−196
36·0	−269

TABLE 4. Continued

Material	Form and Condition	Test Temperature °C	0.2% Proof Stress or Yield Stress MN/m²	ksi	Tensile Strength MN/m²	ksi	Elongation %	Reduction of Area %	Young's Modulus GN/m²	10^6 psi	Shear Modulus GN/m²	10^6 psi	Notched Tensile Strength MN/m²	ksi	Charpy Vee Impact J	ft.lb	Ref.
Nickel/	Sand Cast	20	302.6	44	696.1	101.2	11	9	115.8	16.8	-	-	899.6	105.2	13.6	10	12
Aluminium		-78	328.6	47.8	719.5	104.6	9	9	112.7	17.8	-	-	777.7	112.8	10.8	8	
Bronze		-196	377.6	54.9	605.5	117.1	6	7	127.6	18.5	-	-	819.8	118.9	8.1	6	
		-253	423.7	61.6	870.8	126.6	6	2	127.6	18.5	-	-	839.8	121.8	8.1	6	
		-269	413.4	60.1	897.6	130.5	6	5	127.6	18.5	-	-	816.3	118.4			
Nickel	Bar 19.05 mm	20	144.4	21	440.2	64	48	66	196.5	28.5							13
	Annealed	-78	154.8	22.5	488.4	71	52	66	199.9	29							
		-196	192.6	28	632.8	92	62	75	213.7	31							
		-253	261.4	38	770.4	112	59	67	213.7	31							
Alloy 718	Forging fully	20	997.4	145	1251.9	182	29	44									14
	heat treated	-78	1128.1	164	1368.8	199	27	44									
		-196	1210.6	176	1637.1	238	32	37									
		-253	1279.4	186	1678.4	244	28	38									
Titanium-	Sheet-annealed	20	887.3	129	969.9	141	13	26	106.9	15.5			1110.1	161			15
6 Al-4V		-78	1073.1	156	1148.7	167	11	29	109.6	15.9			1330.7	193			
		-196	1458.2	212	1533.9	223	13	28	115.1	16.7			1744.4	253			
		-253	1788.4	260	1836.6	267	2	3	133.8	19.4			1613.4	234			
3½% Ni Steel	Plate 9.525 mm	21	412.7	60	516.6	75.1	41	75									13
	Normalised and	-75	502.1	73	612.2	89	40	71.5									
	Tempered	-100	542.7	78.9	625.9	91	40	71									
9% Nickel Steel	Plate 12.5 mm	20	619.1	90	770.4	112	22.4	61.7	193.1	28					105.8	78	13
	Normalised and	-78	660.3	96	756.6	119	22.4	-	196.5	28.5					97.6	72	
	Stress Relieved	-196	866.7	126	1169.3	170	29	-	206.8	30					51.5	38	
36% Nickel-Iron	Plate 6-13 mm	20	293.7	42.7	509.0	74	45	72	144.6	21					122.0	90	13
	Annealed	-78	447.1	65	660.3	96	44	70	141.3	20.5					101.7	75	
		-196	646.6	94	880.4	128	42	70	134.4	19.5					65.1	48	
SG Ni-Resist	Cast-normalised	21	223.6	32.5	481.5	70	40	-	117.2	17			339.9	49.3	31.2	23	13
Iron Type D-2M		-196	462.2	67.2	722.2	105	25	-	137.9	20			463.3	67.2	31.2	23	
Stainless	Bar - Annealed	20	227.0	33	584.7	85	60	70	168.2	24.4							16
Steel Type 304		-196	392.1	57	1417.0	206	43	45	180.6	26.2							
		-253	440.2	64	1685.2	245	48	43									
Stainless	" "	20	192.6	28	584.7	85	60	60							149/217	100/160	16
Steel Type 304L		-196	240.7	35	1334.4	199	42	50							122/149	90/110	
		-253	233.9	34	1513.3	220	41	57									
Stainless	" "	20	261.4	38	619.1	90	60	-							149/169	110/125	17
Steel Type 321		-78	343.9	50	963.0	140	49	-							163/230	120/170	
		-196	467.7	68	1444.5	210	43	-							136/163	100/120	
		-253	632.8	92	1637.1	238	35										
Stainless	" "	20	240.7	35	619.1	90	50	60	172.4	25					115/149	85/110	16
Steel Type 347		-196	282.0	41	1279.4	186	40	32	186.2	27					115/142	85/105	
		-253	316.4	46	1451.4	211	41	50									
Stainless	" "	20	240.7	35	577.8	84	70	-							115.3	85	17
Steel Type 316		-78	330.2	48	825.4	120	65	-							137.0	101	
		-196	515.9	75	1272.5	185	58	-							112.5	83	
		-253	577.8	84	1444.5	210	55	-									

An example of the application of 9% nickel steel is shown in Fig. 2, and the cost of this material in comparison with other cryogenic materials is shown in Table 8.

The high nickel—SG Ni-Resist Cast Iron D-2M has found application in cast components of pumps and compressors for cryogenic applications.

Copper is one of the oldest established cryogenic materials[19] and although its high cost and low strength are disadvantages it has good thermal conductivity which alleviates thermal stress. The thermal conductivity of all pure metals increases with decreasing temperature, very pure copper showing a peak value at −261°C, where the value is about 35 times that at room temperature[19]. Small amounts of impurity have a significant effect and with electrolytic tough pitch copper the value is only four times that at room temperature. Nearly all copper and other alloys show a decrease in thermal conductivity with temperature. A typical example of the application of copper in an oxygen plant is shown in Fig. 3 which illustrates a coil containing 7,260 metres (25,000 ft) of tubing.

Aluminium and the non-heat-treatable aluminium alloys have been extensively employed in cryogenic engineering for many years and with the need for alloys of better specific strength, heat-treatable alloys of the aluminium-zinc-magnesium type have been evolved with acceptable low temperature properties.

Austenitic stainless steels, nickel and nickel base alloys such as Monel and Inconel are also important in cryogenic plant. In general all of the stainless steels have acceptable properties but the low carbon varieties such as Type

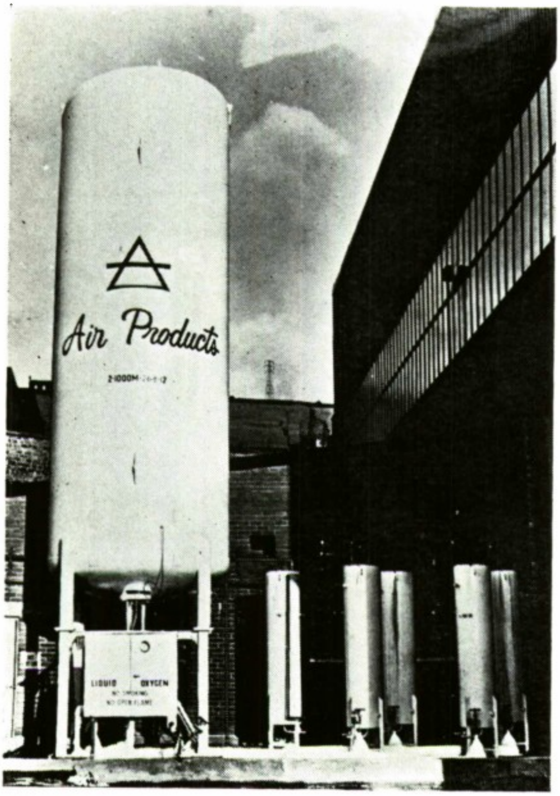


FIG. 2. 9% nickel steel storage tank for liquid oxygen installed in a steel works.
(by courtesy of Air Products Limited)

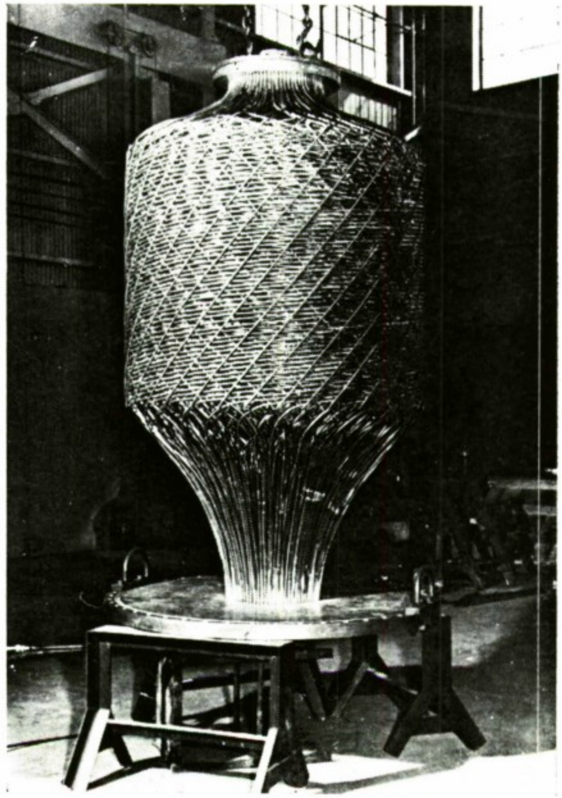


FIG. 3. Copper tube vapourizing coil for oxygen production plant.
(by courtesy INCO Limited and CDA)

304L and Type 316L have the optimum balance of strength, ductility and impact properties coupled with stability against embrittlement during long term exposure or thermal cycling. Austenitic stainless steels suffer in general from low proof stress and in recent years high proof stainless steels[20] based on Types 304, 304L, 316, 316L and 347 have been developed by addition of about 0·2% nitrogen. Such materials are being employed with economic advantage in cryogenic pressure vessels now that design codes permit a proof stress design criterion rather than the former criterion which was unfavourable $\frac{UTS}{4}$ to stainless steels. These stainless steels have proof stress properties about 50% better than similar non-nitrogen bearing materials.

For aerospace applications such as propellant tanks for space boosters, pressure vessels containing liquid gases and high strength fasteners, high specific strength is important. Aluminium alloys and titanium alloys have been employed for tanks and pressure vessels and the high strength nickel-base alloy 718 for bolts[21]. Interstitial elements such as carbon and hydrogen have an adverse effect on the cryogenic properties of titanium and its alloys and extra-low interstitial content materials are employed for aerospace applications. Metal lined glass filament wound pressure vessels have also been studied[22] with the winding adhesively bonded to metal liners of austenitic stainless steel, aluminium alloy or titanium alloy.

For certain cargo tanks in ships the use of membrane tanks[23], where the load carrying function is divorced from the cryogenic containment, is growing in the interests of economy. Membranes may be of Type 304L stainless steel, or 36% nickel-iron. Such liners are corrugated or dimpled to allow for accommodation of differential thermal expansion and may be only 1·25 mm thick (Type 304L) or 0·5 mm thick (36% Ne-Fe). Thicker, plain membranes of 9% nickel steel about 6 mm

TABLE 5. Chemical Compositions of Materials Shown in Table 4.

Material Type	Wrought (W) or Cast (C)	Chemical Composition %																					
		Mg	Mn	Si	Fe	Cu	Zn	Cr	Ti	Al	Pb	Sn	Ni	P	As	C	P	S	Mo	V	H2	B	Nb+Ta
Aluminium BS1470-S1C	W	-	0.1	0.5	0.7	0.1	0.1	-	-	Bal	-	-	-	-	-	-	-	-	-	-	-	-	-
Al Alloy BS1470-N3	"	-	1.0/ 1.5	0.6	0.7	0.15	0.1	-	0.2	"	-	-	-	-	-	-	-	-	-	-	-	-	-
" BS1477 NP5/6	"	3.5/ 5.5	1.0	0.6	0.7	0.1	0.1	0.5	0.2	"	-	-	-	-	-	-	-	-	-	-	-	-	-
" 5083	"	4.0/ 4.9	0.5/ 1.0	0.4 max	0.4 max	0.1 max	0.25 max	0.25 max	0.15 max	"	-	-	-	-	-	-	-	-	-	-	-	-	-
" BS1470-H30	"	0.4/ 1.5	0.4/ 1.0	0.6/ 1.3	0.6	0.1	0.1	0.5	0.2	"	-	-	-	-	-	-	-	-	-	-	-	-	-
" 7039	"	3.0	-	-	-	-	4.0	-	-	"	-	-	-	-	-	-	-	-	-	-	-	-	-
OFHC Copper	W	-	-	-	-	99.95 min	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Admiralty Brass	"	-	-	-	0.03	Bal	27.56	-	-	-	0.04	0.97	-	-	0.041	-	-	-	-	-	-	-	-
Naval Brass	"	-	-	-	0.02	"	39.71	-	-	-	0.09	0.63	-	-	-	-	-	-	-	-	-	-	-
90/10 Cupro nickel	"	-	-	-	1.16	"	0.07	-	-	-	0.02	-	9.98	-	-	-	-	-	-	-	-	-	-
70/30 Cupro nickel	"	-	0.72	-	0.59	"	0.04	-	-	0.01	0.02	0.01	30.05	-	-	-	-	-	-	-	-	-	-
Nickel-Aluminium-Bronze	C	-	0.3	-	3.35	"	-	-	-	9.95	-	-	5.20	-	-	-	-	-	-	-	-	-	-
Nickel	W	-	0.13	0.03	0.14	0.07	-	-	-	-	-	-	99.95	-	-	0.09	-	0.005 max	-	-	-	-	-
Alloy 718	W	-	0.35	0.35	Bal	0.10	-	17/ 21	0.6/ 1.15	0.4/ 0.8	-	-	50/55	-	-	0.3/ 0.10	-	0.015	2.8/ 3.0	-	-	0.002/ 0.006	5.0/ 5.5
Titanium Alloy 6Al-4V	W	-	-	-	0.03 max	-	-	-	-	5.5/ 6.5	-	-	-	-	-	-	-	-	-	3.5/ 4.5	0.0125	-	-
3½% Nickel Steel	W	-	0.63	0.19	Bal	-	-	0.07	-	-	-	-	3.30	-	-	0.1	0.010	0.012	0.10	-	-	-	-
9% Nickel Steel	W	-	0.60	0.30	"	-	-	0.12	-	-	-	-	9.06	-	-	0.1	0.010	0.011	0.04	-	-	-	-
36% Nickel Iron	W	-	0.3	0.3	Bal	-	-	-	-	0.1	-	-	36	-	-	0.1	0.015	0.015	-	-	-	-	-
SG Ni-Resist Iron	C	0.06/ 0.12	3.7/ 4.4	1.9/ 2.6	-	-	-	0.2 max	-	-	-	-	21/24	0.1 max	-	2.2/ 2.6	-	-	-	-	-	-	-
Stainless Steel Type 304	W	-	2.0 max	1.0 max	-	-	-	18/ 20	-	-	-	-	8/12	0.045 max	-	0.08	-	0.03 max	-	-	-	-	-
" " " 304L	W	-	"	"	-	-	-	"	-	-	-	-	"	"	-	0.03	-	"	-	-	-	-	-
" " " 321	W	-	"	"	-	-	-	17/ 19	5xC	-	-	-	9/12	"	-	0.08	-	"	-	-	-	-	-
" " " 347	W	-	"	"	-	-	-	"	-	-	-	-	9/13	"	-	0.08	-	"	-	-	-	-	10xC
" " " 316	W	-	"	"	-	-	-	16/ 18	-	-	-	-	10/14	"	-	0.08	-	"	-	-	-	-	-

TABLE 6. Tipper Notched Tensile Test Data (17).

Metal or Alloy	*Test Temperature °C*	*Maximum Stress MN/m² ksi*	*Elongation %*	*Reduction of Area %*
70/30 Cupro-Nickel	22	361·3 52·4	26	60·5
	—100	433·0 62·8	26	52
	—196	500·5 72·6	27	41
60/40 Brass	20	287·5 41·7	14	26·5
	—120	330·3 47·9	15	27
	—150	347·5 50·4	15	26·5
	—196	384·7 55·8	14	24·5
Type 304 Stainless Steel	18	606·7 88	28	32·3
	— 80	979·0 142	19	19·4
	—120	1,013·5 147	16	17·8
	—196	999·7 145	11	10·6

TABLE 7. Typical Navy Tear Test Data (13, 17, 18).

Metal or Alloy	K_t	Test Temperature °C	Max. Load MN/m^2	ksi	Corrected Energy Values: Initiation J	ft.lb	Propagation J	ft.lb	Total J	ft.lb	Reduction of Plate Thickness
Copper	4	20	146.8	21.3	531.6	392	3032.0	2236	3563.6	2628	52.5[+]
		-150	183.1	26.55	977.7	721	3202.9	2362	4180.5	3083	45.5[+]
		-196	209.6	30.4	873.3	644	4329.7	3193	5203.0	3837	42.2[+]
"	14	-120	193.7	28.1	873.3	644	3705.9	2733	4579.2	3377	49.5[+]
		-196	179.3	26	774.3	571	3267.9	2410	4042.2	2981	41.5[+]
S.G Ni-Resist Iron Type D-2M	4	24	198.6	28.8	192.6	142	732.2	540	924.8	682	16[*]
		-50	229.6	33.3	367.5	271	802.8	592	1170.2	863	17.5[*]
		-196	326.8	47.4	230.5	170	678.0	500	908.5	670	14[*]
	14	24	198.6	28.8	216.9	160	610.2	450	827.2	610	12[*]
		-100	253.3	36.6	359.3	265	989.9	730	1349.2	995	16.5[*]
		-196	301.3	43.7	181.7	134	701.1	517	882.8	651	12.5[*]
9% Nickel Steel	4	16	443.3	64.3	694.3	512	3606.9	2660	4301.2	3172	22.5[+]
		-50	491.6	71.3	1535.0	1132		-	1535.0	1132	17.5[+]
		-100	532.9	77.3	1977.0	1458		-	1977.0	1458	14[+]
		-150	551.6	80	1826.5	1347		-	1826.5	1347	14.5[+]
		-196	588.8	85.4	1052.3	776		-	1052.3	776	7[+]
	14	15	441.9	64.1	581.7	429	2854.5	2105	3436.1	2534	13[+]
		-125	493.0	71.5	637.3	470		-	637.3	470	12.5[+]
		-196	481.9	69.9	237.3	175		-	237.3	175	7[+]
Type 347 Stainless Steel	4	20	279.2	40.5	805.5	594	2472.0	1823	3277.5	2417	31[*]
		-75	361.3	52.4	992.6	732	2431.3	1793	3423.9	2525	20[*]
		-120	366.8	53.2	774.3	571	2375.7	1752	3150.0	2323	16.5[*]
		-140	381.3	55.3	678.0	500	2493.7	1839	3171.7	2339	15.5[*]
		-196	367.5	53.3	374.3	276	1857.7	1370	2232.0	1646	12[*]
Al-4% Mg Alloy		-15	142.0	20.6	179.0	132	768.8	567	947.8	699	11
		-120	156.5	22.7	341.7	252	747.2	551	1088.9	803	13
		-150	155.8	22.6	278.0	205	820.4	605	1098.4	810	13
		-196	158.6	23	146.4	108	610.2	450	756.6	558	14.5

[*] 12.5 mm from root of notch

[+] at fracture

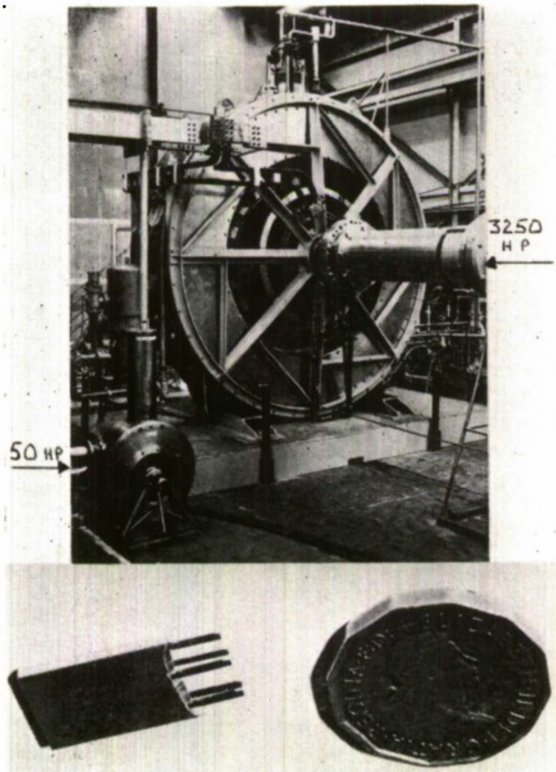


FIG. 4. 3250 HP 200 RPM superconducting motor—1969 with 50 HP "Model" motor—1966 and super-conductor/copper strip winding.
(by courtesy IRD Co. Limited)

TABLE 8.
Comparative Costs of Cryogenic Materials.

Material	*Approximate order of Cost £/ton*
$3\frac{1}{2}$% nickel steel	110 to 150
9% „ „	240 to 300
Aluminium and Al alloys	410 to 570
Stainless steels	430 to 500
36% nickel iron	800 to 900
Copper and copper alloys	900 to 1400
Nickel base alloy 718	~ 4,500
Titanium or Ti alloy	~ 10,000

thick are also under consideration. The low expansion characteristics of 36% nickel-iron (Invar) make it attractive for membrane liners. The high cost (c £800/£900/ton) of Invar also favours efficient usage.

Satisfactory solders and brazing alloys are available for joining cryogenic materials. Soft solders should contain at least 80% lead for temperatures down to −196°C and 90% lead for lower temperatures. Brazing fillers and silver based solders retain excellent ductility at low temperatures but the lead and phosphorous content of the former should be the minimum if impact resistance is to be unimpaired. In general cast materials and weld metal show similar behaviour to comparable wrought materials in Table 4 but the coarser grain size of the cast structure tends to give reduced impact values. Most of the common welding processes are satisfactory but filler materials of different composition to the parent material or of greater alloy content may be required if adequate toughness combined with 100% joint efficiency is to be achieved. For example the 9% nickel steel and Invar are usually welded with nickel-chromium, nickel-chromium-iron, or complex austenitic stainless steel filler. Cast or welded niobium stabilised austenitic stainless steels are not favoured for cryogenic applications since even with carbon limited to 0·5% and niobium to 0·5% impact properties are inferior to those of the unstabilised types. 304L and 316L.

Very pure metals show a dramatic reduction in electrical resistivity at temperatures approaching 0°K. The ratio of the resistivity of HC copper at 293°K to that at 4·2°K may be 300 to 1 and in commercial high purity copper about 1000 to 1. Ultra pure copper may show a ratio as high as 50,000 to 1. Aluminium shows similar behaviour and these two materials offer potential as highly efficient cryo-conductors. Other materials are super conducting below some critical temperature, T_c, which is in the range of 0·01° to 9·15° K for super conducting pure metals and up to 20·7° K for superconducting alloys and intermetallic compounds. The theory and behaviour of superconductors are beyond the scope of this article and it is sufficient to note[24] that such materials are being considered for highly efficient transmission lines and have already been used in powerful magnets and superconducting electrical motors or generators. The IRD Co. Limited 3250 h.p. disc type homopolar motor is the most advanced at present. This machine employs niobium-titanium super-conductor embedded in copper strip and is shown in Fig. 4.

Normal lubricants are not acceptable in cryogenic equipment and hence the cryogenic fluid or gas must be employed as the hydrodynamic fluid. Plastic materials such as PVC or PTFE perform well as bearing materials but have poor abrasion resistance. Thus PTFE impregnated sintered tin-bronze materials have been developed and give satisfactory service. PTFE and also carbon are used in dynamic seals and valves. Gaskets may be of PTFE.

Insulation is extremely important in cryogenic engineering and a wide range of suitable insulation techniques are now available ranging from evacuated jackets to granular solids, mineral wool, glass fibre, inorganic and polymer foams.

Most plastic materials with the exception of PTFE become brittle at low temperatures but glass fibre reinforcement improves their behaviour particularly in relation to thermal shock which may produce cracking in plastics due to their high coefficients of thermal expansion.

Effects of Nuclear Radiation

The first nuclear chain reaction was produced on 2nd December, 1942 and nuclear reactor technology is now almost 30 years old. During this period extensive data have been accumulated on the effect of the various forms of radiation on metallic and ceramic structural and nuclear fuel materials. In addition much information has been obtained on the behaviour of organic materials such as plastics when subject to radiation. As early as 1860 damage arising in minerals containing radioactive impurities had been noted but more complete appreciation of the effects was not obtained until development of the nuclear reactor.

The various types of radiation which are present in a nuclear reactor include fast and thermal (slow) neutrons, alpha particles, fission fragments (from fissioned atoms) electrons, and gamma radiation. The most significant effects in metals and ceramics are produced by the energetic neutrons but gamma radiation can produce considerable damage in organic materials. Energetic (fast) neutrons produce damage by displacing atoms from their equilibrium lattice positions creating vacant sites and interstitial atoms and less energetic or slow neutrons effect changes in the atomic nuclei by capture (absorption) *i.e.*, transmutation.

Thus radiation sensitivity of materials depends on the ease of formation of lattice defects and their subsequent stability. Ceramics exhibit a wide range of bond types including ionic (UO_2), ionic/covalent to covalent (diamond, SiC) and metal carbides show ionic/metallic bonding. The ionic bond is electrostatic and non-directional and this type of lattice can accommodate high distortion without damaging effects. Structures of highest symmetry and closest packing are usually the most stable. The rigid and directional covalent bond is less able to accommodate distortion and hence is more radiation sensitive. Layer type structures such as graphite are subject to anisotropic expansion/contraction effects when irradiated.

In metals the clusters of point defects created by neutron damage interact with dislocations and produce hardening and in some cases embrittlement. Neutron capture or transmutation effects only become significant at high neutron dose levels (c10^{22} or 10^{23} n/cm^2) except in the case of transmutations which lead to formation of inert gas atoms such as helium, neon, krypton or xenon. Most materials contain some small quantities of elements leading to formation of inert gases but it is in fuels and boron containing control rod materials where inert gas problems are most evident although boron in trace quantities can lead to significant embrittlement in structural materials.

Ferritic steels are hardened and embrittled by neutron irradiation and all other metals show similar strengthening but may still retain significant ductility and not show brittleness. Radiation raises the brittle/ductile transition temperature in steels, the extent of this effect depending on total neutron dose, temperature and neutron spectrum (*i.e.* the relative numbers of thermal and fast neutrons). The effect of radiation on the mechanical properties of pure iron and a number of steels is shown in table 9[25] and illustrates that both integrated neutron dose and temperature as well as structural factors such as grain size or the effect of the grain refining additions and general purity level, are influential. Annealing of damage occurs at the higher irradiation temperatures but yield and tensile properties may be influenced more than ductility. Low carbon steels appear more susceptible to loss of ductility than higher carbon materials, possibly because the carbide morphology in normalised steels or the quenched and tempered structures in low alloy steels are more resistant to loss of ductility. Radiation damage effects on yield and tensile properties may saturate at integrated flux dose levels of less than 10^{20} but ductility continues to decrease with increasing dose.

The impact transition temperature of mild, carbon and low or high alloy steels is raised by irradiation and is influenced by similar factors to those affecting mechanical strength and ductility. The maximum ductile energy based on fracture appearance criteria is also reduced. At temperatures below about 260°C irradiation temperature has little influence on the rate of increase in transition temperature with dose, but at higher temperatures the rate of transition temperature rise is markedly reduced, although depending on the temperature of irradiation, there may be no decrease in the ultimate level which will be achieved at high neutron dose levels. Weld metal and heat-affected zones may show a more marked transition temperature rise than parent plate material.

Dose rate has little effect on radiation damage but neutron spectrum has important effects as might be expected. Prior cold-working appears to reduce the extent of irradiation damage in steels and certain other materials.

Irradiation damage in steels can be reduced by post irradiation annealing, damage due to low temperature irradiation being easier to anneal than high temperature damage. Notch ductility may show an initial recovery followed by incidence of re-embrittlement at annealing times longer than about 24 hours and annealing temperatures in excess of 400° C are required to eliminate this effect.

The significance of radiation in raising the transition temperature of steels is in relation to problems of brittle fracture and possible catastrophic failure of reactor pressure vessels. The embrittling effect of radiation may impose problems of restricting the minimum temperature at which an irradiated pressure vessel may be pressurised. The problem can be partially alleviated by employing fine grained or quenched and tempered steels of initially low transition temperature. However safety considerations have led to a preference for reinforced concrete pressure vessels with thin steel (c 12 mm) membrane liners for gas cooled reactors.

Austenitic steels, nickel base alloys and other high temperature materials have been irradiated at temperatures up to 750/800°C and to integrated fast neutron doses in excess of 10^{22} u/cm^2 because of interest in such materials for fuel canning. Whilst tensile and yield properties increase and ductility is reduced such materials do not show a brittle/ductile transition after irradiation. The austenitic steels exhibit a yield point after neutron exposure. Damage in such austenitic materials is not so temperature dependent as in ferritic steels and the high temperature embrittlement effect has been related[26] to the production of helium from the residual few ppm of boron or deliberate alloying additions of up to 100 ppm boron in such materials. Natural boron contains about 18·8% of the boron -10 isotope the balance being boron -11. B-10 has a high capture cross section for thermal neutrons and is transmuted to helium and lithium. Greater purity by vacuum melting and fine grain size are advantageous in reducing the helium induced embrittlement.

Stress relaxation in spring materials under irradiation is greater than purely thermal relaxation and has been explained on the basis of dislocation climb by absorption of irradiation induced vacancies. Certain materials such as Zircaloy may show enhanced creep ductility [27] at stresses between the unirradiated and post irradiated yield stress levels and temperatures below about 0·3 Tm (melting point). In general creep and stress rupture properties may be somewhat degraded in a reactor radiation environment, the creep rate being increased and the stress-rupture ductility being decreased. The effect of radiation on creep behaviour is most marked in certain metallic uranium fuels and in graphite where special mechanisms operate.

Ceramics are important as fuel and moderator materials in nuclear reactors. Metallic fuels and materials such as beryllium may suffer dimensional change (swelling) at high temperatures due to internal production of insoluble inert gases during irradiation and the subsequent creep of the metal matrix due to the internal pressures developed in the gas bubbles which nucleate. Similar effects may occur in high boron steels used in control rods. The solution in the case of fuels has been to use ceramics such as uranium oxide (UO_2), uranium carbide (UC) or uranium dicarbide (UC_2) which permit much higher temperatures and have good fission product retention. Fertile fuel materials such as thorium may be used as the oxide (ThO_2) or carbide (ThC_2) or as

TABLE 9. Effect of Neutron Irradiation on the Mechanical Properties of Pure Iron and a Number of Steels (25).

Material	Neutron Dose n/cm^2 1 MeV	Irradiation Temperature °C	Test Temp °C	Yield Stress or 0.2% Proof Stress* MN/m^2	ksi	Tensile Strength MN/m^2	ksi	Elong %	Red. of Area %
Pure Iron	0	-	R.T.	92.4	13.4	238.6	34.6	60	94
	1×10^{17}	80	"	144.8	21	244.8	35.5	53	92
	2×10^{18}	"	"	268.9	39	289.6	42	36	92
	1.5×10^{19}	"	"	303.4	44	337.8	49	35	91.6
	1.6×10^{20}	"	"	341.3	49.5	379.2	55	34	90
Pure Iron	0	-	R.T.	95.1	13.8		-	-	-
	10^{17}	80	"	148.9	21.6		-	-	-
	10^{17}	150	"	153.1	22.2		-	-	-
	10^{17}	300	"	136.5	19.8		-	-	-
ASTM 212B Steel	0	-	R.T.	345.4	50.1	519.9	75.4	22+	64
(Grain Size ASTM 5)	1×10^{19}	>95	"	450.9	65.4	557.1	80.8	18+	68
Normalised	1×10^{20}	"	"	654.3	94.9	669.5	97.1	5.4+	28
ASTM-A106 Steel	0	-	R.T.	397.8	57.7	519.8	75.4	18.8+	67
(Fine grain ASTM 7)	10^{19}	>95	"	500.5	72.6	540.5	78.4	23.2+	70
(Al grain refined)	0	-	"	326.1	47.3	507.4	73.6	24.5+	-
	10^{20}	>95	"	665.3	96.5	703.3	102	4.5+	-
ASTM-A106 Steel	0	-	R.T.	347.5	50.4	586.1	85	20.2+	67
(Coarse grain ASTM 2)	10^{19}	>95	"	493.7	71.6	617.1	89.5	16+	68
(Si killed)	0	-	"	328.2	47.6	572.3	83	19+	-
	10^{20}	95	"	799.8	116	834.3	121	1.5+	-
ASTM-A106 Steel	0	-	R.T.	275.8	40	524.0	76	18+	-
(Fine grain ASTM 7)	2×10^{19}	305	"	558.5	81	703.3	102	8+	-
	2×10^{19}	360	"	379.2	55	599.8	87	11+	-
	2×10^{19}	405	"	330.9	48	565.4	82	12+	-
	8×10^{19}	305	"	544.7	79	730.8	106	6+	-
	8×10^{19}	415	"	324.1	47	544.7	79	11+	-
ASTM-A106 Steel	0	-	R.T.	317.2	46	551.6	80	14+	-
(Coarse grain ASTM 2)	2×10^{19}	305	"	641.2	93	792.9	115	8+	-
	2×10^{19}	360	"	461.9	67	675.7	98	9+	-
	2×10^{19}	405	"	296.5	43	579.2	84	14+	-
	7×10^{19}	305	"	599.8	87	710.2	103	3+	-
	7×10^{19}	415	"	441.3	64	648.1	94	11+	-
8.5% Nickel Steel	0	-	R.T.	632.9	91.8	820.5	119	29.5	21.5+
	1.7×10^{19}	>95	"	951.5	138	1,020.4	148	18	11+
	1×10^{20}	"	"	1,261.7	183	1,268.6	184	5.5	2+

+ Uniform elongation prior to necking.

mixed carbide ($(UTh)C_2$) or oxide ($(UTh)O_2$). For high temperature control rods where swelling of boron would be significant the use of boron carbide powder contained in a metal case, with a vent hole to release any inert gas escaping from the powder, has been found to be simple and effective.

Graphite has been used as the moderator material in many gas cooled and other reactor types and because of its anisotropy as normally manufactured it undergoes dimensional change when irradiated with neutrons. Such effects are temperature dependent with expansion at low temperatures and contraction at high temperatures depending on the extent of preferred orientation. This problem has led to the development of so-called isotropic graphites with improved radiation stability particularly at high temperatures. A further effect in graphite is the "Wigner effect" where low temperature irradiation leads to a build-up of stored energy. Raising the material to a higher temperature results in release of this energy and if the rate of release is not controlled by careful attention to heating rates then, due to the low specific heat of graphite, excessive temperatures may be generated. The elastic modulus and electrical restivity are also raised by irradiation and the thermal conductivity is reduced.

Silicon carbide either as a self bonded material or as a pyrolytic coating and also pyrolitic carbon are finding application in high temperature reactor fuels as noted earlier. Preferred orientation and crystallite size have important effects on the irradiation behaviour of pyrolitic carbon and the best properties are achieved in isotropic deposits.

Conclusion

The rapid development of new materials has largely kept pace with the demands of modern technology and there is no shortage of available materials having the correct balance of properties for engineering applications under a variety of extreme conditions of environment. Demands may be even more onerous in the future but with the application of the new materials available at present and those which will become available in the future as a result of the continuing high level of research and development in materials science, it would appear that problems will be solved by the combined ingenuity of the materials technologist and the designer.

Acknowledgements

Acknowledgement is made to Director AML for permission to publish this article. The contributions of all those who have provided information, advice and assistance with illustrations is gratefully acknowledged.

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NEW U.S. RESEARCH VESSEL — R.V. *A. B. WOOD II*

Mrs. Ethel M. Wood, widow of Dr. A. B. Wood has received a request from Tracor Mas, formerly Marine Acoustical Services Inc. of America, for permission to name a new oceanographical research ship the R.V. *A. B. WOOD II*. This vessel is to replace the one launched in 1965 and named in honour of Dr. A. B. Wood for his life long work in underwater acoustics.

The Supply of Gas Mixtures at Constant Oxygen Partial Pressure to Semi-Closed Circuit Breathing Apparatus

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Royal Naval Physiological Laboratory

Abstract

A method of supplying a variable gas mixture to a semi-closed circuit breathing apparatus is described. The supply system is designed such that the gas mixture in the counter lung will have an oxygen partial pressure, Po_2, which is relatively constant and independent of depth.

This is achieved as follows. The total gas mixture is regulated to supply the set with a constant volume flow measured at the prevailing ambient pressure (i.e. a total mass flow variable with depth). The supply of oxygen to the set is at a constant mass flow at all depths. Oxygen is supplied via a constant mass flow jet (commercially available). Oxygen and inert gas (N_2 or He) is then supplied to the counter lung via a laminar flow element. The supply of inert gas is regulated to ensure a constant pressure drop, ΔP, across the laminar flow element and hence a constant volume flow of gas mixture.

Design theory and calculations are presented. An experimental model of the system has been constructed and tested over the range 1 to 7 atm. The results obtained indicate that the theoretical system described for supplying a gas mixture at constant Po_2 to semi-closed circuit breathing apparatus can be reproduced in practice.

Introduction

At present there are three main classifications of breathing apparatus in use in Great Britain. These are open circuit, closed circuit and semi-closed circuit.

Open Circuit

In open circuit operation the diver is supplied with gas from a cylinder, *via* a demand valve and exhaled gas is exhausted into the water. Whilst open circuit apparatus is adequate for shallow diving—down to 100 ft., beyond this depth the duration time of self-contained sets is very limited. Duration problems may be overcome by using umbilical supply to the apparatus. For oxygen-helium diving (*i.e.* beyond 200 ft.) this type of operation becomes very expensive and wasteful.

Closed Circuit

The main advantages of closed circuit apparatus are low gas consumption, long endurance, and freedom from the restraint of an umbilical. The gas breathed by the diver is re-circulated through a counter lung and a soda lime canister to remove CO_2. Oxygen partial pressure, Po_2, in the gas mixture is sensed by electrodes and kept within fixed limits by an electrically controlled oxygen injection system. At present these sets are under development and are not commonly in operational use. The main drawbacks are the relative complexity of the system as opposed to open and semi-closed sets, and high price.

Semi-closed Circuit (Constant Mixture Supply)

Semi-closed circuit sets practically eliminate the disadvantages of open circuit sets mentioned above and are simpler, more robust and much less expensive than the closed circuit sets. Most of the gas is re-circulated through a counter lung and soda lime canister as in closed circuit apparatus, but a constant supply of gas is added to the system on the inspiratory side. Consequently there is a small but constant quantity of gas exhausted to the water. These sets are most commonly used as umbilical supply but are also available as self-contained sets. Most deep diving operations at present are carried out using semi-closed circuit apparatus.

The main limitation of the semi-closed circuit set lies in the fact that it is supplied with a fixed gas mixture at a constant mass flow. As the gas mixture is constant the Po_2 of the supplied gas increases with depth. Gas mixture and flow rate requirements vary with depth and therefore for one set of conditions there is a limited range of operation (see Fig. 3). The range of operation for a given mixture and flow rate is calculated to supply gas to the diver at a Po_2 of 0.2 to 1·75 atm. Gas mixture to the set and the mass flow jet must be altered to conform with dive depth. In addition, such a variation of Po_2 further complicates the calculation of correct decompression times. The standard equation utilised to determine Po_2 in the set (certain approximations accepted) is as follows:

$$Po_2 = \frac{0{\cdot}01\,xL - Y}{L - Y} \times \frac{(D+33)}{33} \quad \ldots (1)$$

where x=oxygen %
Y=oxygen consumed
L=supply flow of gas mixture
D=depth in feet sea-water

It is in this respect that closed circuit equipment is superior to semi-closed circuit—a range of gas mixtures do not have to be stocked, and the Po_2 is kept fairly constant.

Design Theory for a Variable Mixture Supply Semi-Closed Circuit Set

In order to overcome the problem of gas mixture supplied to the semi-closed set at various depths it would be necessary to supply the set with a mixture which changes in relationship to the depth. To obtain a condition where the Po_2 in the set is fairly constant at all depths it would be required that oxygen was supplied to the set at a constant mass flow rate, but the inert gas (*e.g.* N_2 or He) was supplied at a flow rate proportional to the absolute pressure, *i.e.* to produce a constant volume flow rate of gas mixture at any given pressure.

The proposed design comprises a method of supplying a variable gas mixture of constant oxygen partial pressure to a divers' semi-closed circuit breathing apparatus wherein the oxygen is supplied *via* a constant mass flow device, mixed with an inert gas and the mixture supplied *via* a laminar flow device, the supply of inert gas being regulated to ensure a constant pressure drop across the laminar flow device. Fig. 1 shows a block diagram of such a gas mixture supply system.

Referring to Fig. 1, the counter lung of the semi-closed circuit breathing apparatus is supplied from a bottle of oxygen (1) and a separate bottle of inert gas (2). The oxygen is passed through a regulator (3) and is metered by a mass flow jet (4) to give a constant mass supply to the counter lung (5). The inert gas is passed through a regulator (6) and a regulator (7) and then with the oxygen through a laminar flow element (8) to the counter lung (5). By using the regulator (7) to produce a constant pressure drop, ΔP, across the laminar flow element (8), at all depths there is a constant volume flow of gas through the element to the set. For laminar flow through a tube, flow, q, is regulated by the equation:

$$\frac{\Delta P}{1} = \frac{8\mu}{\pi a^4} \times q \quad \ldots (2)$$

where μ=gas density 1=tube length
a=tube radius.

In this manner at any given pressure the gas mixture supplied to the set would have a constant Po_2.

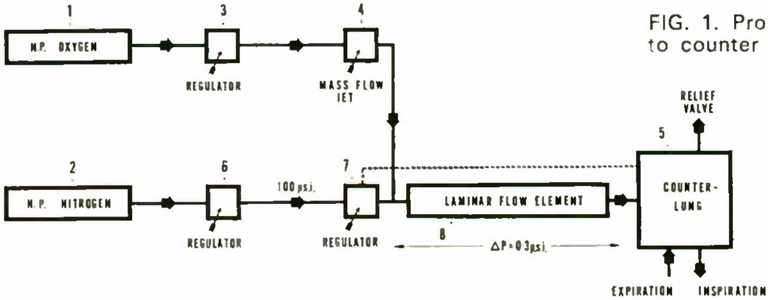

FIG. 1. Proposed variable mixture gas supply to counter lung.

Example 1

In order that the proposed design may be more fully understood one embodiment thereof is described by way of example. Using an oxygen-nitrogen gas mixture from surface to 200 feet (7 atm abs) the following flow rates could be applied.

Total volume flow to the counter lung= 8 l/min. (ambient pressure, temperature).

Mass flow of oxygen to counter lung=4·8 l/min. (at 1 atm, ambient temperature).

Appendix 1 shows the relevant calculations for Po_2 in the counter lung under these conditions. It is assumed that oxygen consumption by the diver is in the range 0·25 l/min. to a maximum of 3·0 l/min. (at 1 atm, ambient temperature).

Laminar Flow Element

A laminar flow of 8 l/min. up to a pressure of 7 atm abs can be obtained by passing the gas mixture through a series of small bore tubes arranged in parallel. The number of tubes, pressure drop, length and the diameter required to give the correct flow conditions is dependent upon the following equations and equation (2).

$$N_R = \frac{\rho d \bar{v}}{\mu} \quad . . . (3) \qquad Q = \frac{\pi d^2}{4} \bar{v} \, n \quad . . . (4)$$

where

ρ=gas density	Q=volume flow
d=tube diameter	n=number of tubes
N_R=Reynolds Number	$\bar{v}$=velocity

Due to the effect of density on Reynolds Number, N_R, in order to produce laminar flow (N_R <2000) of 8 l/min. at 7 atm abs the element would have a laminar flow capacity of 56 l/min. at 1 atm abs. The number of tubes required and their diameter can be derived either by calculation or from experiment. Fig. 2 shows a graph relating pressure and flow for 20 tubes of 1 mm. internal diameter. At 1 atm abs flow is laminar to 20 l/min. Using 60 tubes therefore would give laminar flow of 8 l/min. at 200 ft. Using tubes of 1·2 metres in length gives a pressure drop of 0·3 psi (20 cms. H_2O) across the element which can be maintained at all depths using a commercially available regulator. By arranging the tubes in a circular form (<40 cms. diameter) the flow element would be compatible with the dimensions of conventional semi-closed circuit sets.

Fig. 3 shows the relationship of Po_2 at the counter lung to depths for a conventional semi-closed (constant mass) apparatus and a proposed variable mixture apparatus. The graph depicts a conventional apparatus supplied at a mass flow of 50 l/min. of air and is suitable for use from a depth of 9ft. to 200ft. Over this range Po_2 may vary from 0·20 to 1·45 atm. Most semi-closed sets are supplied with mixtures at a lower flow rate resulting in an even greater variation of Po_2 with depth. The Po_2 in the counter lung of the proposed variable mixture supply apparatus is based on the calculations of Appendix 1. As can be seen from Fig. 3, Po_2 in the counter lung is virtually independent of depth and in this respect is similar to a closed circuit set.

Similar calculations can be presented for oxygen-helium mixtures for diving to depths beyond 200 ft. As the viscosity of oxygen, nitrogen and helium differ by less than 20% the same set could be used for either oxygen-nitrogen or oxygen-helium diving. For oxygen-helium diving in the range of 150 ft. to 600 ft. further economy of gas could be achieved by reducing the number of tubes (and hence flow) in the laminar flow element.

Experimental Development

Having established the dimensions required for the laminar flow element, a test model of the projected supply system described in Example 1 was constructed. A photograph of the experimental model is shown in Fig. 4. For test purposes, the laminar flow element was constructed in brass and consists of 60 tubes of 1·0 millimetre internal diameter and 1·2 metres in length. Mass flow of oxygen supplied to the laminar flow element is controlled by the regulator and mass flow jet AP 7658 as used in R.N. Clearance Divers Breathing Apparatus (semi-closed circuit set). High pressure nitrogen is supplied *via* a BOC regulator (not shown in Fig. 4) at 100 psi above ambient to a second low pressure regulator TEKNOVA type 230B. This regulator was attached to the nitrogen inlet of the laminar flow element. The regulator was adjusted to give the required pressure drop to approximately 0·3 psi above ambient. In order to obtain feed-back at the low pressure regulator of the outlet pressure from the laminar flow element the adjusting cap of the regulator was replaced with an O ring seal. Outlet pressure from the laminar flow element was then supplied to the low pressure regulator as the refer-

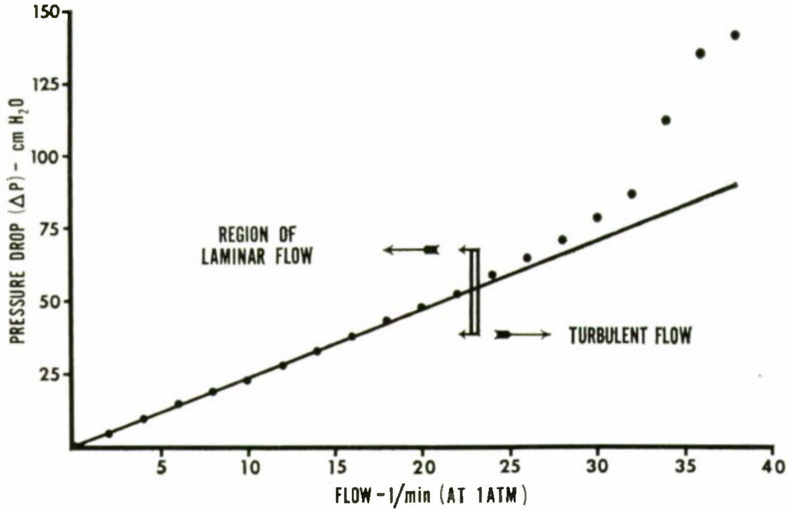

FIG. 2. Calibration of a laminar flow element during a dive to 4 atm. Element: 20 tubes of 1 mm. internal diameter and 1·2 metres length.

ence ambient pressure through a tapping in the casing of the regulator.

To test the stability of the system under pressure a series of dives was carried out in a pressure chamber. The system was adjusted at surface to supply a mass flow of 4·8 ± 0·1 l/min. of oxygen and a total flow of 8·3±0·1 l/min. of gas mixture (both quantities measured at ambient temperature and pressure). A water manometer was connected across the laminar flow element and the outlet was connected to a dry gas meter. Gas flow and pressure drop were measured at 60 second intervals over a period of five minutes at each depth. Measurements were taken at surface, 33 ft., 99 ft., 150 ft. and 198 ft. (equivalent depth of sea water).

It was found that there was a slight drop in the downstream pressure maintained by the low pressure regulator which resulted in a corresponding drop in the volume flow through the laminar flow element. Experimental results from surface to 198 ft. are shown in Fig. 5.

A second series of experiments was conducted in which a gas sampling point was inserted at the outlet from the laminar flow

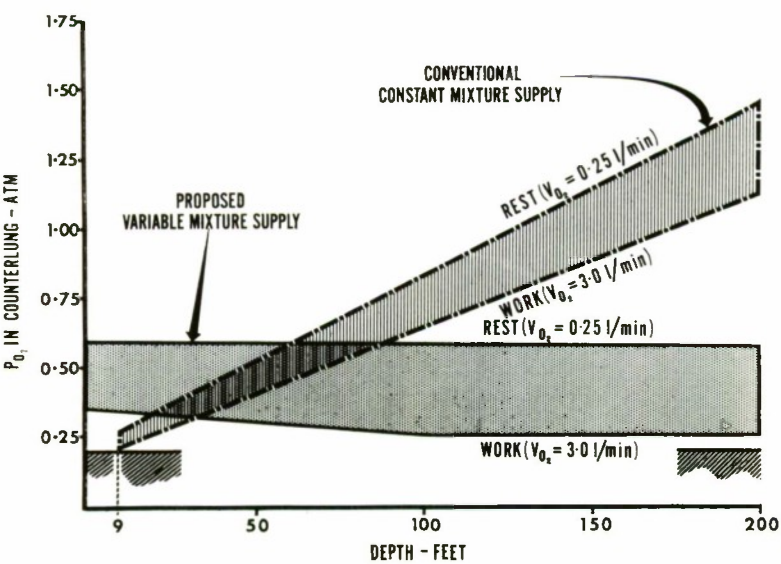

FIG. 3. The relationship of P_{O_2} in the counter lung of semi-closed circuit apparatus to depth. A comparison of a conventional mixture supply system (mass flow 50 1/min. of air) and the proposed variable mixture system (Example 1).

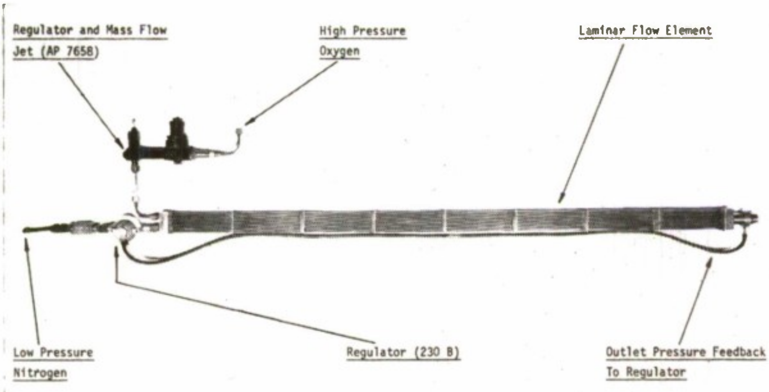

FIG. 4. Experimental model of gas supply system.

element. At each depth gas samples were bled from the sampling point through a valve in the wall of the pressure chamber and collected in stainless steel cylinders. The gas samples were analysed using a Perkin-Elmer F11 gas chromatograph.

A gradual rise in partial pressure of oxygen, Po_2 from 0·57 atm at surface to 0·66 atm at 198 ft. was recorded. As the mass flow remains relatively constant the rise in Po_2 with depth results from the drop in total gas flow measured. The total gas flow and Po_2 measured during these experiments are shown in Fig. 5. Analysis of Po_2 in the gas mixture, on different occasions, showed a maximum variation of $\pm$0·03 atm at 198 ft. The limits of Po_2 measured at each depth are given in Fig. 5. This variation in Po_2 at a given depth is considered to be due mainly to a slight variability in the oxygen supply from the mass flow jet over the experimental period.

The measurements of pressure drop across the laminar flow element, total gas flow, and gas mixture composition obtained from the experimental model in this series of experiments demonstrate that the theoretical principles discussed in the first part of the report can be reproduced in practice. The variations of Po_2 in the gas mixture supplied by the model do not significantly affect the principle of the supply system. Applying the total gas flow and mean Po_2 measurements taken from the model to the calculations of Appendix 1 would

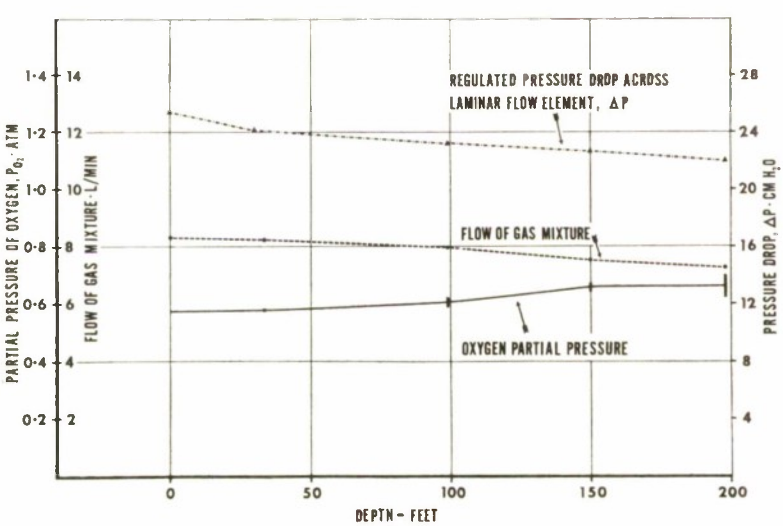

FIG. 5. Variation with depth of (a) Pressure drop ΔP across the laminar flow element, (b) Total gas flow (ambient temperature, pressure) and (c) P_{O_2} in the gas mixture supplied.

result in a range of oxygen partial pressure in the counter lung of 0·26 to 0·63 atm as opposed to the theoretical range of 0·24 to 0·59 atm shown in Fig. 3.

Conclusions

The results obtained from the experimental model of the gas mixture supply system indicate that the design theory developed for supplying a variable gas mixture of constant Po_2 to semi-closed circuit breathing apparatus is feasible in practice. With suitable re-design the test system used could be reproduced in dimensions compatible with a standard commercial, semi-closed circuit breathing set.

Acknowledgements

The authors wish to thank Mr. W. S. Butt and Mr. B. McNaughton for the design and construction of the laminar flow device tested, and Mr. J. Florio for undertaking the analysis of gas mixtures.

APPENDIX 1.

Calculations for Example 1 and Fig. 3

$$Po_2 = \frac{0{\cdot}01\ xL - Y}{L - Y} \times \frac{(D+33)}{33}$$

where L = supply flow 1/min. at 1 atm.
Y = oxygen consumed 1/min. at 1 atm
x = % oxygen in mixture supplied

at surface: Supply = 8 litres 1/min. (ATP)
∴ L = 8 1/min.
4·8 1/min. O_2 ∴ x = 60

for Y = 0·25 $$Po_2 = \frac{0{\cdot}01 \times 60 \times 8 - 0{\cdot}25}{8 - 0{\cdot}25} \times \frac{33}{33} = 0{\cdot}59 \text{ atm}$$

for Y = 3·0 $$Po_2 = \frac{0{\cdot}01 \times 60 \times 8 - 3{\cdot}0}{8 - 3{\cdot}0} \times \frac{33}{33} = 0{\cdot}36 \text{ atm}$$

at 99 ft. (4 atm): Supply = 8 1/min. (ATP)
∴ L = 32 1/min.
4·8 1/min. O_2 ∴ x = 15

for Y = 0·25 $$Po_2 = \frac{0{\cdot}01 \times 15 \times 32 - 0{\cdot}25}{32 - 0{\cdot}25} \times \frac{99+33}{33} = 0{\cdot}57 \text{ atm}$$

for Y = 3·0 $$Po_2 = \frac{0{\cdot}01 \times 15 \times 32 - 3{\cdot}0}{32 - 3{\cdot}0} \times \frac{99+33}{33} = 0{\cdot}25 \text{ atm}$$

at 200 ft. (7·06 atm): Supply = 8 1/min. (ATP)
∴ L = 56·5 1/min.
4·8 1/min. O_2 ∴ x = 8·5

for Y = 0·25 $$Po_2 = \frac{0{\cdot}01 \times 8{\cdot}5 \times 56{\cdot}5 - 0{\cdot}25}{56{\cdot}5 - 0{\cdot}25} \times \frac{200+33}{33} = 0{\cdot}57 \text{ atm}$$

for Y = 3·0 $$Po_2 = \frac{0{\cdot}01 \times 8{\cdot}5 \times 56{\cdot}5 - 3{\cdot}0}{56{\cdot}5 - 3{\cdot}0} \times \frac{200+33}{33} = 0{\cdot}24 \text{ atm}$$

STRESS WAVE ANALYSIS

(or " taking the pulse of a structure ")

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R. H. Warren, B.Sc., Ph.D., A.I.M., R.N.S.S.
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This article is about a new method of NDT.

It is a matter of common experience that structures such as bridges and pressure vessels " creak " under excessive load or when approaching the end of their life, and that they often emit several loud noises (like pistol shots) just before they finally fail; these noises are the result of bursts of stress waves being emitted from discontinuously growing defects.

By listening to such noises (which are detectable from the onset of microstructural damage), we hope to be able to determine both where and how severe the defects are in a structure.

This article describes the present state of the art in the use of stress wave analysis applied to fabricated structures—with particular emphasis upon the MOD(PE) Structural Validation research programme at AML, and with some warning on difficulties associated with the use of the technique.

Like any other new technique, it will complement existing (NDT) techniques, not entirely supplant them. Immediately, it offers a much quicker and cheaper method for finding defects, and one which can sometimes be used to reach areas inaccessible to any other method of NDT, but it will be some years before we also learn how to make it tell us all about the significance of each defect.

Introduction

This brief article is a second progress report on our work, the first being given under the title " Structural Validation " in the *J.R.N.S.S.* Vol. **25**, No. 6, of which the section " The Future " on page 312 provides a linking introduction to this note, and which will not therefore be repeated.

In noting that propagating defects give rise to noise, it is necessary to realise that the emission of noises from a structure does not necessarily presage imminent failure. Wood is a notoriously noisy material when bent, yet, as Professor Gordon has pointed out, the creaking from the wings of wooden gliders is a reassuring sound, and the pilot would probably be deafened before the wing spars snapped !

The subject of stress wave emission analysis as we know it today really began with the Ph.D. Thesis of Kaiser[1], who was the first to use electronic amplification to listen to materials under varying loads. He studied a wide range of materials, and found (among other things) that if the load was removed and re-applied, very little noise was emitted until the original load was exceeded. This became known as the " Kaiser Effect ", which further study has shown to be (like so many illuminating characteristics of the state of a material), much less simple and useful than at first hoped, being particularly susceptible to strain-aging and recovery effects. Dunegan and others in the U.S.A. showed that high frequencies (up to 3 - 5 MHz) could be used, and this permitted the technique to be used in

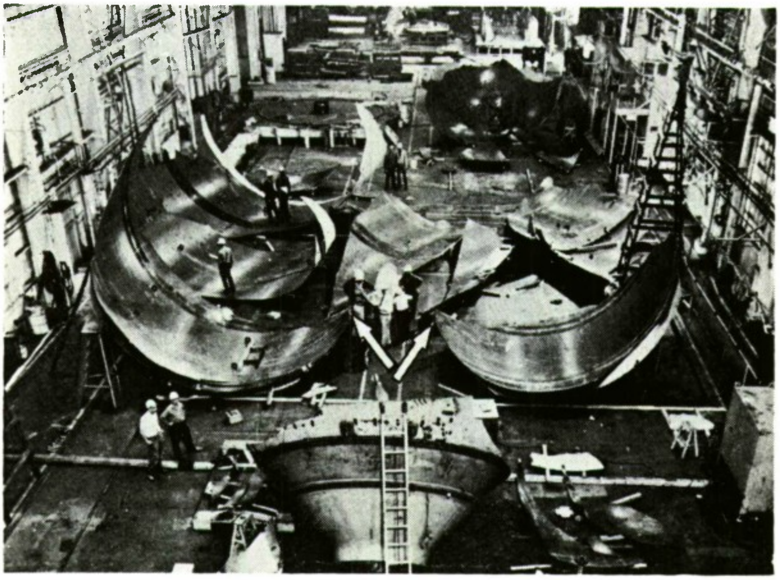

FIG. 1. Failed motor case with pieces laid out. Origin of fracture indicated by arrows.
(Reproduced by permission of N.A.S.A. from Report T.M.X.-1194).

noisy environments, since ambient and machinery noise levels are rarely troublesome at such frequencies, it also meant that experimental work need no longer be confined to silent hours!

From this modest beginning, and particularly under the impetus of the American space programme, enormous strides were made in America in studying stress wave emission (called Acoustic Emission, Stress Wave Analysis Technique, or SWAT over there) as a result it is now a very fashionable subject, often used with the other high fashion subject of "fracture toughness", in attempts to study and predict the behaviour of expensive components fabricated in exotic materials.

Fig. 1 shows a 260 in. rocket motor case. which, when subjected to a routine hydrotest, failed in a dramatic manner in 1965[(2)]. It just so happened that stress wave sensors had been applied to the vessel as part of a developing research programme into SWAT and merely taking advantage of the pressure test, and by the time the engineers had looked at the bits and worked out where the failure had started two very significant things had happened. Firstly, the investigators using stress wave emission had predicted the probable position of the source and were found to be correct within a few inches (Fig. 2), and secondly, the proponents of linear elastic fracture mechanics had calculated the critical defect size for failure under the conditions of the test, and they were also shown to be very near the mark.

This fortunate accident had the predictable result that many people became fanatical advocates of either or both of these new techniques, equipment suppliers mushroomed, and minor fortunes were made and lost—together with reputations; we have now reached a stage in the U.S.A. where the mistakes, misapplications and disillusionments which inevitably accompany the over-enthusiastic adoption of any new idea, coming together with the cutback in expenditure on advanced technology, has brought the sceptics and critics to the fore, so that the claims and counter claims made for and against the use and capability of stress wave analysis are now at full blast, and it is probably easier to find a critic of the subject than it is to find an avowed convert.

In this country, interest in stress wave analysis was slow to start, but within the last five years has been gathering momentum until now there are a number of centres in the country where SWE is the subject of research, and is even in limited use. At AML we firmly believe in the value of stress wave emission analysis when intelligently applied, but we are also convinced that a great deal needs to be learnt and much caution is necessary in the use of this technique. We believe too that engineers are now in the fortunate position of being able to stand on the shoulders of those who have pioneered so many of these techniques in the U.S.A. and that the whole subject of Structural Validation (the term we have coined to describe a deliberately positive approach to

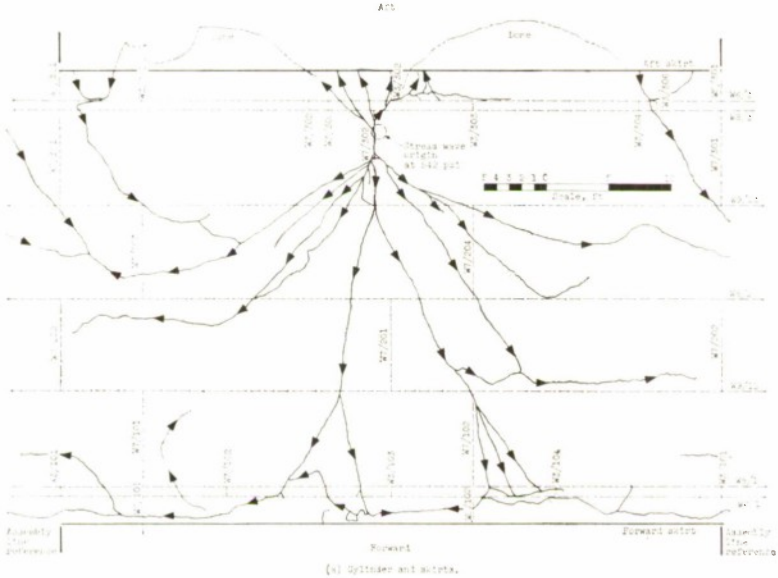

FIG. 2. Map of fracture paths as viewed when looking at inside surface of the vessel. Arrowheads indicate directions of fracture propagation.

(Reproduced by permission of N.A.S.A. from Report T.M.X.-1194).

proving the fitness of a structure, in contrast to the negative approach inherent in NDT where one finds flaws without prior regard to their significance), is now capable of being taken some dramatic and cost-effective steps forward, and that one of the most powerful tools by which this will be done is through the use of stress wave emission phenomena.

Stress Waves

Stress wave emissions themselves are complex shock waves which originate within materials due to discontinuous relaxation phenomena at growing defects. These emissions propagate throughout the structure in a variety of wave modes; in plate and shell structures the energy is transmitted by wall to wall reflections, each accompanied by complex wave mode conversions such that the effective group velocity is that of the bulk shear wave. The initial burst of energy from the extending defect contains a wide and continuous band of frequencies, but attenuation, interference and multiple reflection phenomena mean that very little energy above a few MHz travels more than a few metres in the structure.

It has been found that the passage of the complex group wave which radiates from a growing defect can be detected by a suitably mounted piezoelectric transducer on the surface of the material, with a typical response as shown in Fig. 3.

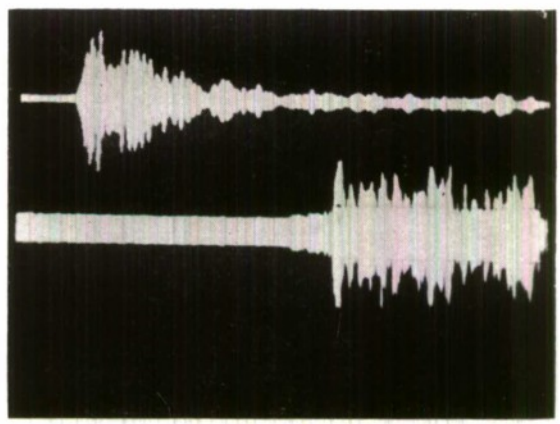

FIG. 3. Typical stress wave sensor responses. Upper trace: from a nearby source (timebase 1 m sec/cm, vertical scale 100 μV/cm). Lower trace: the first part of the response to a stress wave from a distant source (timebase 1 m sec/cm, vertical scale 10 μV/cm).

Once detected, the information can be used to provide an idea of the number and magnitude of such emissions, or by using a group of transducers and suitable timing techniques to indicate the probable source of such emissions.

Analysis Systems

Stress wave analysis systems can range from a gramophone pickup linked to a simple audio amplifier, in a total system cost of under £10, having a correspondingly limited potential (but nevertheless capable of very

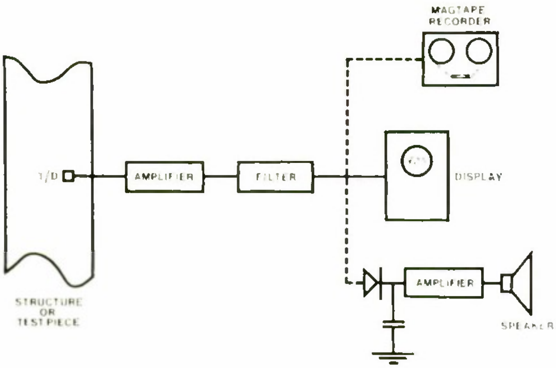

FIG. 4. Simple Stress Wave Emission Equipment.

dramatic performance and, incidentally, a very useful "educational" aid), or the equipment may be rather more adaptable at a cost of £100-£2,000 using equipment linked together as shown in Fig. 4 and used to study crack iniation and propagation by stress-corrosion or fatigue, in laboratory tests or in large structures, or it can be developed as a special purpose instrument such as the prototype Mark 2 AML Weld Quality Monitor shown in Fig. 5 costing less than £500, or it may range up to a highly expensive and very sophisticated source location and grading system having a computer on line, such as the AML SVS Mark 1 system now being built (shown in block form in Fig. 6) and costing anything from £30,000 for this system to £200,000 or more for some systems of similar capability already developed in the U.S.A.

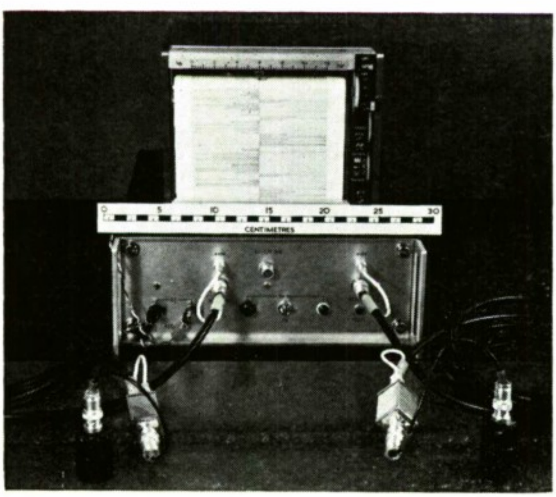

FIG. 5. AML Mark II Weld Quality Monitor.

But like any other form of non-destructive testing it requires several things; in addition to equipment, technical knowledge and people, it requires proper management, and the management of stress wave analysis depends in turn upon a knowledge of what the technique can do.

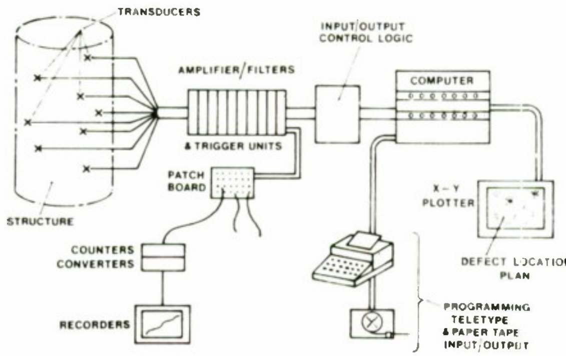

FIG. 6. The AML Defect Location System.

What Stress Wave Emission Analysis Can Do

From an engineering standpoint, and particularly from an economic standpoint, a major attraction of stress wave analysis over other systems of non-destructive testing is that it is a passive method of interogating a structure, which enables the structure to tell us both *where* and *how much* it hurts; thereby avoiding the need for a great deal of time-consuming inspection for defects, using search tools having small areas of influence. It also has the advantage that if a defect is not extending in some way, we shall not learn that it is there. This carries obvious hidden dangers, but provided that the stresses being applied to the structure during the time of testing, (and this is an important distinguishing characteristic of the way in which stress wave emission examination must be used—in conventional NDT, service loads are normally absent during the inspection) one could have a relatively large "defect" in a structure (which is, however, innocuous due to its position, etc., and the service stresses in its vicinity) and therefore, since it will not be extending at the time of inspection, SWE will not detect it. So a potentially attractive feature of SWE analysis is that it will not tell us about things which we do not really need to be kept awake at night worrying about!

The Promise

But its most attractive feature is that it offers a potential approach to the crux of one of our most pressing problems in NDT and quality control, that of establishing the significance of defects.

Linear elastic fracture mechanics and its plastic derivatives can best be applied to materials of very limited ductility, but most engineering is (fortunately) associated with materials having high ductility, in which it is difficult to calculate critical defect sizes, but in which one must take cognizance of sub-critical extension processes, since eventually any defect which is growing will reach a critical size. One way of defining whether or not a defect is significant in a large structure is to say that it is only significant if it will, of itself, trigger failure of the structure, or if sub-critical defect flaw growth can conceivably cause it to grow to a size sufficient to cause failure before the next inspection (see LEO Technique)[3]. In either case, under service or simulated service loading the defect will only extend if it is "significant", and because it is growing (albeit on an infinitesimally small scale) the stress waves which it emits enable us to detect and/or locate it, and this, coupled with the ability which we are rapidly acquiring to grade the severity of the defect, is the big prize offered by research into stress wave emission from fabricated stuctures.

The Problems

In research one must be careful to temper enthusiasm for the potentiality of new ideas with consideration of the difficulties which always attend their adoption as dependable pieces of technology. There are many problems in the use of stress wave analysis, but two are specially worthy of mention.

In a complicated structure, noises will be generated from rubbing interfaces (at joints, around rivets, control mechanism spindles etc.) and whilst a computer and software package can be arranged to tell the system to ignore signals from such sites, there are obvious limitations, and even dangers in this process. As a result, some structures (such as riveted aircraft structures) may not readily be inspectable by the techniques at present available.

The other major problem arises from the enormous dynamic range of signals ($\sim$10,000 : 1) from extending defects. This results in problems of determining the best way of assessing both the precise origin and the amount of noise coming from each defect, and our solutions to this problem are as yet inexact.

Acknowledgement

This article is based upon a presentation by the authors to a Group Discussion at the Institution of Mechanical Engineers on 23rd September 1971, but much of the work and philosophies described was contributed by our friend and colleague Peter Wingfield who died on 14th December 1971. Our future progress will be slowed by this tragic loss, just as our daily tasks are no longer enlivened by his infectious good humour and stimulating inventiveness.

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MACHINERY SEATINGS FOR SURFACE SHIPS

Reported by L. S. LePage, B.Sc., F.R.I.N., R.N.S.S.
Admiralty Engineering Laboratory

A very successful conference on this subject was held at the Mechanical Department of the Admiralty Engineering Laboratory. West Drayton, on September 21st-22nd, 1971. It was attended by a strong team led by Mr. J. H. Janssen from the Technisch Physiche Dienst Tno-Th of Delft, and by representatives of AEL, AML, ARL, AUWE, DGS, DNPR, NCRE, Imperial College, Southampton University (Institute of Sound and Vibration Research), Messrs. Plessey Ltd. (Marine Systems Research Unit), and Yarrow, Admiralty Research Department.

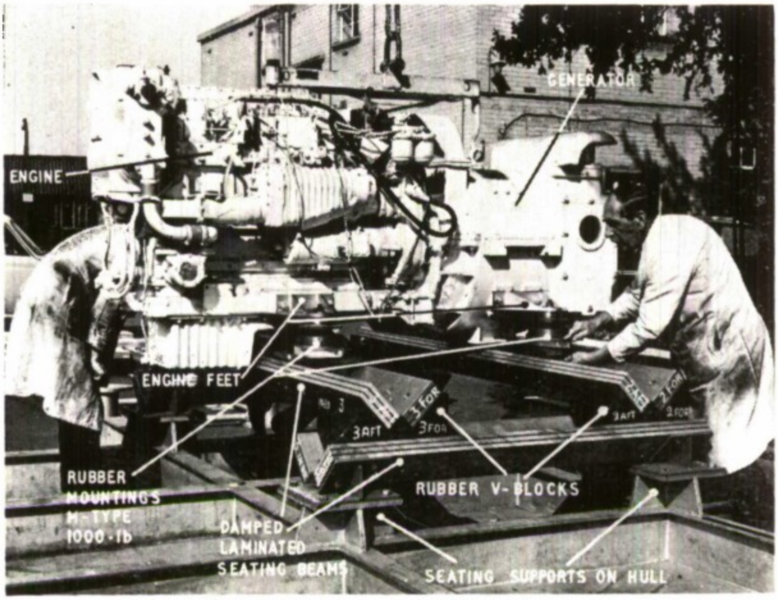
Introduction Some words of explanation for the holding of this Conference may be appropriate. Current practice when installing most machinery in a ship is to provide a mild steel (or in some cases a non-ferrous) framework bolted or welded to the hull or to the deck, of sufficient rigidity to support the machine in its correct static position, and strong enough to withstand a specified degree of shock. The mechanical design of such a seating takes no account of whether noise transmission from the machine to the hull is of significance or not. Attenuation of machine vibration levels was for long considered to be the sole prerogative of the flexible mountings which may be inserted between the machine and its seating, and which of course also accept the weight of the machine. Possibly 40dB of attenuation can be obtained in some instances by the use of such mountings. In many instances however this sort of attenuation cannot be achieved, because of low values in parts of the spectrum of the mechanical impedance presented by the seating.

It is now recognised that as the seating forms part of the main path of the structure-borne noise from machine to hull, its design from an acoustic point of view should not be left to chance. For example, it is undesirable that any natural resonances of the seating should coincide, or nearly do so, with any of the forcing frequencies in the vibration spectrum of the machine.

If, therefore, attention is to be given to the acoustic design of seatings, the following aspects must be considered:—

(i) the choice of materials,
(ii) the general design, which will depend upon the vibration characteristics of individual types of machine,
(iii) the mechanical impedance of the hull supporting the seating,
(iv) techniques for measuring mechanical impedance,
(v) evaluation and reduction if necessary of the effects of parallel paths by means of which energy may be transmitted to the hull,
(vi) techniques for evaluating the performance of the seatings.

These, then, were the subjects discussed at the Conference. The eventual aim would be, given the machine characteristics, the mountings performance, hull impedance, and the radiation characteristics of the hull, to provide a theoretical design of a seating such that the oscillatory pressure in the water attributable to the machine would not exceed a given target level for radiated noise. The attainment of such an aim is however not yet in sight. Clearly also there is a similar requirement in respect of self-noise attributable to machinery.



An experimental damped seating for a Foden F.D.6 diesel-generator unit.

Outline of Conference

The discussions emphasised a considerable divergence of opinion on the part of the various workers in the field. This was often a result of generalised statements made on measurements circumscribed by definite boundaries. Apparently conflicting viewpoints could possibly be reconciled if the limits of each statement were recognised.

Only a few of the subjects discussed will be dealt with here. Mr. S. J. O. Tinn of AEL opened the Conference by giving a description of current work and philosophy. He considered the seating impedance should be as high as possible; the stiffness should be at least 10 times as high as that of the rubber mountings. Machinery rafts, if used, should be well damped. Machines should never be mounted on top of tanks (*e.g.* lubricating or fuel oil) if this was at all avoidable. The effect of direct transference of airborne energy from machine to hull could in some cases vitiate any structural attenuations in certain frequency bands, and measures to reduce airborne noise might have to be adopted. This point was echoed by other speakers. As regards impedance measurements, there was a requirement to be able to make these in high noise backgrounds.

Dr. P. Grootenhuis of Imperial College said that there was a strong probability that as many degrees of freedom were involved, at least one might present a low impedance, hence an acoustically-designed seating was essential. He urged that it was necessary to "let the seating move" if it was to dissipate energy by means of damping.

Mr. J. E. Holton stressed the necessity of looking at the seating as a dynamic structure. A static mass of 600 lbs, for example, might be the equivalent of only a few ounces at a particular frequency. Each transmission path was best dealt with separately. He instanced work done at AEL in which a lead mass in a double-mounting system was applied below each foot of a refrigerator, resulting in an attenuation of 74dB at the higher frequencies.

Mr. H. F. Steenhoek, of TPD, dealt with the problem of reliably evaluating the performance of seatings. The conventional procedure for measuring transfer functions from machine to sea, was to relate force applied to the seating to pressure measured at a hydrophone. To do this satisfactorily meant measuring six input components (three directional forces and three couples) with their phase relationships. It was far better to invoke the reciprocity principle, and to use a hydrosounder in the sea to produce a signal which could be detected by accelerometer pick-ups on the seating. By using this technique and changing the seatings, it ought to be possible to evaluate the seatings and put them in order of merit. A description of the actual techniques used, and the instrumentation employed, was given by Mr. Steenhoek.

Mr. Tinn followed with a description of work in H.M.S. *Penelope* using a damped seating consisting of aluminium beams in conjunction with PVC sheeting so as to form multi-layer sandwiches. A reduction of the order of 12dB in hull vibration was observed, compared with the use of a conventional steel seating, even though only one of the six modes of vibration had been dealt with. It also appeared that in spite of noise reduction measures, energy transferred to the hull by airborne noise in the ship now dominated the underwater frequency spectrum at nearly all frequencies.

Mr. ten Wolde of TPD, also referred to work on this seating compared with an undamped seating using the reciprocity technique. The damped seating was to some extent better in respect of underwater noise, but there were many exceptions in the transfer functions; in fact it could not be stated that this seating gave a definite improvement in underwater noise and he suggested that shorting due to airborne noise was the probable cause.

A description was given by Mr. A. Stride of AEL of impedance measuring techniques, with a survey of experimental work and the results obtained. Mr. J. Bone, also of AEL, described the damping of an engine raft, using a constrained layer technique together with injection of the cavities in the raft with a damping foam devised by AML.

The difficulties of obtaining a suitable damping material for incorporation in seatings were then examined by Mr. E. T. Clothier of AML. Damping compounds were normally temperature conscious, and some were susceptible to the liquids found in conjunction with machines. To obtain a compound which was efficient at the low temperatures which might prevail at a machinery seating (if in contact with the hull, for example) a plasticiser might be incorporated in the compound, but this would eventually come out in the course of time, or if affected by oil or water.

Mr. J. Donaldson of NCRE thought that moments were not as important as forces at low frequencies. He also argued that vibrating forces were of primary importance, not energy, and that forces transmitted to the hull control the underwater noise energy almost independently of hull impedance. He was much concerned about the shorting effect of airborne noise, citing a case in which he had found it necessary to encase a vibration generator in a steel box to avoid noise effects.

Dr. D. Ewins, of Imperial College, stated that an initial mathematical model had been made, taking relevant parameters of the machines, seating and hull into account. This was being developed, taking into account further degrees of freedom.

Dr. R. White, of ISVR, described the fast frequency sweep method of measuring impedance, which had been developed by ISVR under contract to AEL. He stated that the frequency range 10 - 1000 Hz could be swept in one second, a typical sweep time for a practical test. With a computer, analysis could be performed in 20 seconds using a fast Fourier transform.

A number of different designs of seating were exhibited. One such, developed by Imperial College for a Foden FD6 Diesel-Generator Unit, is illustrated on page 141.

Conclusion

The Conference served a most useful purpose in bringing together those working in this field, and in helping to indicate the directions in which progress can be made.

CORRESPONDENCE : LETTER TO THE EDITOR

D. Mussett—An Appreciation

Dear Sir,

I worked with **Douglas Mussett** from January 1941 to March 1954 except for a short period after the war, and so he played a major part in my professional life. I have always been grateful for what he taught me and for the encouragement and opportunities he gave me. We met again regularly in the 1960s on a GCHQ advisory panel and this cemented a long friendship which ended with his death in January of this year, only 14 months after his retirement.

He was a remarkable man in many ways. First and foremost he produced ideas in a constant stream and followed them with tenacity and purpose, whatever the difficulties and discouragement. He would do this with the bad ideas as well as with the good ones, and caused some minor storms, but oddly he seemed to generate new good ideas out of what seemed to others to be dead ends. He was never happier than when playing with electronics. He produced circuits that worked, by empiricism and experience that were at once the wonder and fury of his colleagues: wonder, because they seemed impossible, and fury, because they were difficult to repeat and sometimes impossible to put into production.

His energy seemed unlimited. During the war, he was capable of working 48 hours without sleep, and I have been driven by him on long journeys interspersed with all night meetings and operational equipment investigations. He also had endless patience. He would explain and re-explain technical matters, which I, working as a mathematician and analyst, had to understand, and, in the end, he saw that I did.

I have always felt that the "system" was unkind to Douglas. He was unconventional and would sometimes fight too hard with wrong arguments because he hated to admit defeat. But he was often right when no-one listened, and a lot of equipment and ideas are still in service because he worked hard, thought hard, and never gave up.

As a leader his zeal was infectious. Many who worked for him and with him will remember him for a long time, for what he gave to them and for what he was, a kind friend and most able colleague whose enthusiasm and devotion to his work never diminished. As one of the few of his wartime colleagues still in the business, I salute his memory on behalf of all—and I sign myself as I was then known by him and my fellows.

"K.C."

NOTES AND NEWS

Admiralty Materials Laboratory

Mr. W. Sweasey (Bill) retired on February 9th 1972 after 34 years continuous service with the Admiralty.

He commenced his service career as an Engine Fitter Apprentice in H.M. Dockyard, Portsmouth in 1922 but, in company with the rest of his entry, was a casualty of the "Geddes axe" in 1928. He returned to the Dockyard in 1938 when the rearmament programme was developing. He joined the Torpedo Tube Design Section as a temporary draughtsman and eventually found his way to the Underwater Launching Establishment, West Howe, Bournemouth as a confirmed draughtsman.

He joined A.M.L. Holton Heath in February 1952 as a leading draughtsman, in charge of the Design Office, and was promoted to Senior Draughtsman in 1966.

He was disestablished in February 1969 and continued to serve in A.M.L. Design Office until his retirement.

The photograph shows the Director, Dr. R. G. H. Watson, presenting him with a gold wrist watch and with it goes his colleagues appreciation of his efforts on their behalf and their best wishes for a long and happy retirement which he and his wife will no doubt fill with interest.

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Admiralty Surface Weapons Establishment

Mr. W. D. Delany and Mr. H. E. Walker attended the Third Tripartite Conference on NBC Ship Defence held in Washington in November. Mr. Walker presented a paper on the Vulnerability of Shipborne Equipment to EMP. Mr. G. W. Murray and Mr. B. A. Cox visited the Royal Norwegian Naval Base at Haakonsvern, Bergen in January 1972. Communications equipment developed in the establishment was fitted on the submarine RNM *Svenner* and trials were carried out off the Norwegian coast It. is hoped that this visit will result in sales of the equipment to the Norwegian Navy for fitting throughout their submarine fleet.

Two leading Draughtsmen on the establishment's staff have recently retired after extensive periods of service to the Crown. Mr. William Nuttal, completed nearly 44 years service with the Admiralty, and Mr. William Leonard Spells completed almost 50 years, 21 of which were in the Navy itself.

It is reported with pleasure that Mr. Ivor Allison, a Senior Draughtsman with the establishment's Installation Division, was honoured with the award of an MBE in the New Year's Honours List. Mr. Allison joined the Service in 1949, and although an arthritic sufferer, he has shown outstanding courage and cheerfulness in difficult circumstances which have marked his devotion to duty as exemplary.

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Admiralty Underwater Weapons Establishment

On 10 November, 1971, Mr. W. K. Grimley, O.B.E., Head of Sonar Department, was guest of honour at a luncheon at Laboratoire de Detection Sous-Marine, Le Brusc. Ingénieur Générale Lozachmeur, of Dcan Toulon, paid tribute to Mr. Grimley's outstanding contribution to Anglo-French collaboration in the Sonar field since 1949 when he was a founder member of the present organisation. Mr. Grimley was presented with an official plaque of Dcan Toulon (see photograph).

Mr. F. S. Burt, Deputy Director A.U.W.E., succeeds Mr. Grimley as U.K. Chairman, Sub-committee "S"—Anti-submarine Detection.

L. J. Fitzgerald retired at the end of January after 32 years service. Previous to joining HM Signal School in 1939 he had 12 years training and commercial experience in the production and distribution of non-ferrous metals for the electrical and radio industries. He was always interested in radio and is an enthusiastic "ham" with contacts in all parts of the world.

Most of his first 12 years in the RNSS were spent at Eastney Fort East and the King Edward VI School at Witley, which had been taken over for use as experimental laboratories after the Signal School was evacuated from Portsmouth as a result of enemy bombing. During these years he was associated with the development of the early, metric, air warning radar for submarines.

Towards the end of 1951 he transferred to Portsdown and was engaged on the development of the second generation (centimetric) submarine radar system. The trials and tribulations to be overcome were many, not only because of the special environmental problems posed by submarines, but also because of the inexperience of some of the contractors. When this radar programme was completed, "Fitz" was transferred in 1961 to the communications division for development work on digital data link terminal equipment, and in 1964 he undertook what was probably his most difficult assignment as U.K. project leader for the very large and complex Anglo-Dutch radar known as *Broomstick*, and was promoted CXO. When, in 1968, the RN decided to terminate their participation in the project, "Fitz" spent a few, relatively quiet, months on the study of a replacement for Type 965 until he became, in 1969, Head of the Handbook Group, which post he held until his retirement.

Fitz was always a pleasant and helpful chap to work with. He is quite a philosopher and can always add point to a discussion by quoting apt similies on a *reductio ad absurdum* principle. His standards were always of a high order and his departure has left a large gap amongst his many friends in ASWE.

BOOK REVIEWS

The Encyclopaedia of Marine Resources. Edited by Frank E. Firth. D. Van Nostrand Co. Ltd.; 1970. Pp. xi + 740. Price £11·70.

This book represents an attempt to supply in one comprehensive volume the accumulated facts and figures of the marine environment. Such a generalisation of subject matter will therefore include such diverse topics as, for example, pure biology, heat and power from the sea, undersea mining, conchology, fishing statistics, and very many others, involving in all, more than one hundred and twenty-five subjects of current interest.

Almost all aspects of the marine sciences and technologies are currently being developed and exploited more exhaustively than probably any other section of the physical environment, and discoveries and advancements are being recorded almost daily. The coverage given to the commercially important natural resources, and the causes and effects of the very modern problem of polution provide examples of the up-to-date information which is provided, and for which there is always demand.

When considering a book of this type, one must realise from the start that much detail will have to be sacrificed in order to accommodate such a wide range of subject matter. It is obvious that specialised text books will give a more exhaustive and complete coverage of a particular topic, but this book makes up for this in the only way possible, by giving a number of references after appropriate sections. The careful selection of these references is very essential if the compromise between detail and range of coverage is not to detract from the value of an encyclopaedia, and the depth of references cited in this book reflects the painstaking editing that has gone into it.

The other great drawback with encyclopedic books is, alas, almost unavoidable, *viz* the rapid obsolescence of data. Information such as catches for the last financial year is of little or no value five or ten years later, and the best way of dealing with this problem (apart from the publication of supplements) is to keep this type of data to a minimum. This has clearly been in the minds of the authors, and essential details liable to early change are often accompanied by similar data taken earlier, enabling the rate of change to be seen, and later values to be estimated.

The subjects are dealt with in strict alphabetical order, with an average of slightly under six pages per topic. As well as the references described above, cross references to other related sections of the book are given where appropriate. There is an abundance of drawings, charts, graphs, maps and photographs, all superbly presented as would be expected in a book of this price.

All in all, the book provides a most adequate work of reference which will be of great value in the library of any organisation to whom marine resources are of interest.

J. R. Kirby

Cybernetics Simplified. By A. Porter. Pp. 159 + x. London. English Universities Press. Price £1·10.

Readers of this review will know that cybernetics is the name given to the whole field of control and communication theory whether in machine or in the animal. But the term cybernetics is not yet in such common usage that authors feel it unnecessary to begin with a definition of its meaning, and thus, because of its title, this book may not find its way into the hands of a number of people who would find it extremely useful. Such people are those requiring an introductory text on control systems, servo mechanisms, and modelling techniques.

In the first chapter Professor Porter introduces feedback with examples taken from different fields, and this is followed by a brief account of the evolution of automatic control devices and computers. The measurement of variables and the transmission of the information are the next topics, the accelerometer and the synchro are described, time delays are mentioned as are the analogue and digital methods of transmitting signals.

A whole chapter is then devoted to servo mechanisms because Professor Porter believes it is important to understand the operation of the simple servo mechanism in order to understand the appreciably more complex cybernetic systems of life and society. In the next chapter the use of models in science, engineering and economics is outlined, and also in this chapter flowgraphs (which show the scheme of dependence between key variables) are introduced. Stability and methods of stabilisation are considered in Chapter 6, and finally there is a chapter on the learning process showing the application of feedback, and including some notes on the use of models in the study of learning.

Professor Porter based his book on a series of lectures given to a group of enthusiastic sixth form students, and he intended it to be an introductory primer to a vastly proliferating field of science and engineering. It is, in fact, an excellent book, interesting and instructive, and should fulfil the intended purpose admirably. Mathematical symbols make an appearance on a few pages, but not in sufficient quantity to deter even that mythical reader—the intelligent layman.

J. B. Spencer

The Mechanical Properties of Matter. M. T. Sprackling. English Universities Press, 1970. Pp. xii + 144. £1·30.

This book is one of the Bridge series which is intended for students of sixth-form standard to " bridge " the gap between school and college. It deals with the physical properties of solids, liquids and gases, and considers how these properties may be regarded as dependent on molecular forces and energy.

After a brief introduction into the nature of the states of matter, first to be considered is elasticity, including stress and strain, moduli of elasticity, Poisson's ratio, elastic limit and yield point, and elasticity and tensile strengths of liquids.

The permanent deformation of solids is then covered, incorporating tensile tests, plasticity, dislocations and work hardening. Ductile and brittle fractures are introduced together with the ductile-brittle transition.

Liquid viscosity is then introduced, defining coefficient of viscosity, and then considering critical velocity and the dependence of viscosity on temperature. Shear, non-Newtonian liquids, liquid flow through tubes and the effect of particles are discussed, and a brief account of commercial viscometers concludes this section.

Gases are discussed, with mean free path, gas viscosity and its measurement and streamline flow through a tube.

Surface effects is the last main section, and this deals with free and total surface energy, liquid spreading, capillary rises, variation of surface energy with temperature and the measurement of free surface energy for liquid/vapour interfaces.

At the end of each of the main sections, there are worked examples, problems for the student to solve and then suggestions for further reading. The answers to the problems with hints are given at the end of the book.

Obviously with such varied subject matter being dealt with in so small a book, each topic has only very brief coverage, but this is compensated for by much concentration of detail within the text. It will be of considerable use to "A" level physics students particularly as an aid to revision for examinations. The price is very attractive, and all in all it is a very worthwhile publication.

J. R. Kirby

Semiconductors and Semimetals. Vol. 5, Infrared Detectors. Pp. xiv + 551. Edited by R. K. Willardson and A. C. Beer. Academic Press. £12·15.

This book, the fifth in this series on semiconductors and semimetals, differs considerably in content from Volumes one to four. The earlier books dealt with the physics of the materials studied, exclusively iii-v semiconductors. This book is the first of a number dealing with applications of the properties of semiconductors.

The editors state that there will be additional chapters on infrared detection in later volumes of this series. This book is not therefore a comprehensive treatment of semiconductor infrared detectors, even if this is implied in the title. However, the topics that are treated are covered, generally, in considerable depth and provided that a particular subject of interest is included in this book, then it is covered at a level that should satisfy a research worker. This is accomplished by allowing each chapter to be written by an acknowledged expert in that field. As a whole, this necessarily results in a somewhat disjointed treatment of infrared detectors.

As the treatment is not comprehensive, it is essential for an intending purchaser to know the content of the book. Several other books provide the overall view of infrared detector technology with far fewer gaps and in much more accessible form. This is a book for a specialist in particular detectors.

The characterisation of infrared detectors is covered by the first, and shortest chapter. This chapter could profitably have been three times as long, and have covered some general topics such as the theory of photo-conductivity and heterodyne detection which are later covered several times by different authors.

A full and detailed treatment of InSb detectors follows, limited to photoconductive and photoelectromagnetic detectors. Photovoltaic InSb detectors are to be covered by a chapter in a later volume. Next narrow band self filtering detectors are described. These are sensitive only to photon energies close to to the band gap energy.

Long wavelength mixed crystal photodetectors occupy the next two chapters on Lead-Tin Chalcogenides and Mercury-Cadmium Telluride. On the whole the treatments given are suitably comprehensive and cover material preparation to theory and practice in infrared detector properties. Unfortunately practical values of D* are not included on HgCdTe.

The next two chapters do not refer at all to semiconductors or semimetals, being on pyroelectric detectors and radiation thermopiles. If these detectors are to be described in this book, then surely a place should be found for other bolometric techniques. Apart from this criticism, the two topics are treated well.

In spite of their titles, the next three chapters are essentially on uses for doped Germanium photodetectors. The first of these chapters has an excellent introduction to the problem of attaining background limited detection, and a description of the problems of low level incoherent detection. The rest of this chapter, and the next two chapters, cover coherent detection. There is unfortunately a lot of repetition as the authors tackle the same problems, even one diagram is repeated. If any reader is interested in detection of CO_2 laser radiation with doped Germanium photodetectors, the answer should be contained in this section.

The next chapter contains a most readable treatment of microwave biased photodetectors, followed by a final chapter on a rather unusual topic, imaging and display. The imaging described is mainly the near visible infrared, and displays are hardly directly relevant to infrared detectors. This chapter in particular tended to describe some particular devices or techniques to the exclusion of others.

As a whole, this book is not limited to semiconductors and semimetals, and is not a treatment of infrared detectors. It is, however, an excellent book for anyone with an interest in those topics it does cover, and amounts to a series of review papers on these subjects. For the serious research worker on these topics it would be an excellent buy.

B. R. Holeman

NOTICE TO READERS

The Editor extends to all readers of the Journal and particularly those of the younger generation, a cordial invitation to contribute articles of R.N.S.S., naval or general scientific and technical interest.

Authors are requested particularly to note that as the Journal is in the Restricted category the printing of material within its pages does not constitute open publication and does not prejudice the subsequent use of the material in the Journal of a learned society or institution, or in the scientific and technical press.

Manuscript should be typewritten if possible, in double spacing and on one side of the paper only. It should include, in addition to the title, the name of the Author together with initials, degrees and department, establishment or ship. Pseudonyms are acceptable only in special circumstances. A convenient length is between 3,000 and 5,000 words, but other lengths are acceptable and no contribution would be debarred on this ground alone. Illustrations are in most cases a desirable addition. Photographs should be of good quality, glossy, unmounted and preferably between two and three times the size of the required final picture. Graphs and line drawings should be made on a similar large scale, with bold lines to permit reduction in block making. A recent photograph and biographical note of the Author(s) will also be welcomed.

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